Computational Synthesis for Scientific Experimentation

Siu-wai Leung

Doctor of Philosophy

Centre for Intelligent Systems and their Applications
School of Informatics
University of Edinburgh

2007

Abstract

This thesis presents a new use of computational synthesis for scientific experimentation, particularly synthesis from parameterisable experiment protocols. An experiment protocol, in addition to its own specific materials and methods, can incorporate modular protocols and can be made modular to be used by other protocols. Two synthesised Web-based experiments for cognitive science were conducted to demonstrate the practicality of experiment synthesis - obtaining significant scientific results. Our conceptual model of experiment protocols as specifications (in a logic programming style) leads us to use conditional rewriting techniques for logic program synthesis in synthesising experiment setups from experiment protocols. A method of conditional rewriting and stepwise refinement of an abstract experiment protocol is specified using grammars with optional feature structures. Specific rewrite rule conditions including selective mappings between feature structures of protocols determine whether and how protocol rewriting is performed. Following simple grammars, the setups of the exemplified experiments were synthesised, including Websites as materials, experiment procedures as methods, and cognitive tests as protocol modules. Two synthesised cognitive science experiments on causal perception and design preference were conducted to test the effects of rhetorical (temporal and causal) and modal (tabular and graphical) presentation of information. In the causal perception experiment, the test subjects could not differentiate the effects of temporal and causal rhetorics in presenting aviation accident information. However, their ratings on causality based on the covariation between potential causes and consequences gave evidence for a better agreement with the Power PC theory of causal perception (compared to the others assessed and still under dispute) in aviation accident reporting (a different test scenario). In the design preference experiment, more people prefer graphical to tabular presentation. Despite the high preference for graphical presentation, the given tabular presentation was generally rated to be easier than graphical presentation to interpret, especially for those who score below average in the visualisation and analogy-making tests. This piece of evidence helps generate a hypothesis relating design preferences to specific cognitive abilities. Without the use of computational synthesis, the experiment setups and scientific results would be impractical to obtain.

Acknowledgements

I am grateful to Dave Robertson, my supervisor, for his encouragement, guidance, insights, patience, and support throughout my PhD study. I would not have started my PhD study without his encouragement. I would not enjoy academic research so much during this period of study without his insightful advice and helpful guidance. Without his great amount of patience and support, I could not have survived from various difficulties and finished my thesis.

I thank all the persons, including my parents, my brothers, my fellow PhD students, my fellow researchers in Edinburgh (or around me through Internet), my current and former colleagues/co-workers (particularly office mates), and my other friends, who have been giving me valuable advice, sharing with me their experience, and turning my life tribulations into grateful joys.

I thank my wife Ivy and son Ian, who have sacrificed so much for me to study.

Parts of this work has been supported by EPSRC grant GR/M98302 for research on Communicating Knowledge about Accidents from Synthesized Websites.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(Siu-wai Leung)

Table of Contents

Chapter 1

Introduction

Science tries to produce plausible representations of the world under investigation. The plausibility of the representation is judged with respect to reality (by realists), consensus (by relativists), and/or usefulness (by pragmatists). The investigation is usually conducted under strict control according to reliable scientific practices. Probably the most reliable scientific practice is experimentation, which places the hypotheses (e.g., testable theories, knowledge, and beliefs) before the tribunal of experience, i.e., controllable, sharable, and replicable observations. However, even though science employs experimentation, technical solutions to issues such as reproducibility, generalisability, reliability, and causality are not yet readily available.

This thesis presents a new use of computational synthesis for scientific experimentation, particularly synthesis from parameterisable experiment protocols, in order to facilitate synthetic experiments which may help improve the generalisability and thus reliability of science. It also presents two experiments synthesised to test established theories of causal perception and to test the correlation between cognitive factors and design preference. Causal perception serves as a cognitive basis for science. The causal perception experiment explored in this thesis is a Web-based experiment making use of computational synthesis. The design preference experiment reuses the Website synthesiser in the causal perception experiment to generate preferred Websites on the fly.

This chapter gives an overview of this thesis; in particular the motivation for using computational synthesis to facilitate cognitive science experiments.

1.1 Problems in Scientific Experimentation

Science usually describes categories (universals) rather than individuals (particulars / specifics). While we can only study individuals (particulars / specifics), generalisation from some individuals (particulars / specifics) to categories (universals) is necessary. Scientific experimentation produces reliable evidence for testing hypotheses/theory and facilitating the generation of new hypotheses. However, due to resource constraints, it is difficult to conduct experiments that can avoid sampling errors. Without proper sampling, it is unreasonable to claim that the sample represents the target population. The experiment findings are thus difficult to generalise. For the notorious problem of induction (as discussed by David Hume[1]), experiments with limited samples can only falsify hypotheses (Popper, 1959) rather than confirm hypotheses. Particular setups and instruments based on specific theories may not enable unbiased (theory-free) observations in testing hypotheses. With its interventive nature, experimentation is supposed to be more reliable than simple observations. However, the intervention of experiments can only isolate confounding factors for better observation of covariation. It does not guarantee causality findings, which are only subjectively perceived through causal perception based on covariation. There may be uncontrollable factors affecting the experiments; thus, experiment findings may need replication to ensure their reliability. Some local experiment practices may be difficult to transfer to other laboratories, especially those that require tacit knowledge (Sahdra and Thagard, 2003); thus, replication may not be easy. Even if the experiment findings were reliable, they are subject to expert evaluation (e.g., peer reviews), coherence with other evidence, and argumentation before acceptance by the scientific community. Sometimes, the beliefs of the experts in addition to the experiment findings influence the acceptance of some hypotheses or theories. Personal preference, social forces, and political influences may change the perception of the experiment findings. Rhetoric often is useful in argumentation for or against greater acceptance of particular theories. Thus theory-laden experiments can be considered as part of the scientific argument to resolve disagreements and justify the reliability of hypothesis testing. While a hypothesis/theory is only a tentative explanation, the life spans of experiment findings as well as contextual experimental informa-

[1] `http://www.etext.leeds.ac.uk/hume/ehu/ehupbsb.htm`

tion (such as experiment protocols) last longer because they should make sense (be explainable somehow) in new theories. Experiments help develop and extend the representational capacities of science (e.g., through novel or improved instruments) but the high cost of scientific experimentation hinders full scale testing of hypotheses/theories. Improvement in the effectiveness, efficiency, and economy of experimentation thus helps improve scientific research.

A basic element in ensuring the reliability of experimental results is to do further experiments in the same, similar, and coherently broader or deeper ways. Extensive and systematic experimentation is desirable as it introduces more constraints and criteria in testing plausible theories (Haack, 1995, 2004). However, experiments are expensive to design, prepare, and perform. Experiments are not easy to set up for the first time and they are not easily reproducible for later verification and modification. This thesis uses computational synthesis to facilitate experimentation. Particularly, the experiments presented in this thesis use Web materials that are very difficult and tedious to prepare if we do not use computational synthesis. This is an example for how technology helps improve science.

1.2 Computational Synthesis of Experiments

Despite the fact that informatics has provided some solutions to support scientific experimentation, particularly for laboratory management and instrument control, little attention is paid to the synthesis of experiments. Laboratory information management systems (LIMS), including laboratory workflow management systems, statistical experiment design systems, etc., provide scientists with the tools to manage experiment data, operate specific instruments, and monitor progress. Domain-specific programming or scripting languages are available for setting up laboratory instruments. For example, an instrument scripting language may be used to control a specific instrument. Web scripting languages control the Web environment for Web-based experiments. It is desirable to have a single/unified declarative knowledge representation for scientific experimentation, which would enable computational synthesis of experiments based on various conceptual models such as purposes, processes, functions, structures, components, etc. Hence in this thesis we develop a grammar-like rule syntax for knowledge representation/specification, and to demonstrate that important parts of experiments can be computationally synthesised.

1.2.1 Advantages of Experiment Synthesis

Computational synthesis of experiments provides two main advantages, higher productivity and better reproducibility, compared to the manual synthesis of experiments. These features tend to increase the quantity and quality of evidence obtained from experimentation in science.

1.2.1.1 Higher Productivity

Computational synthesis expedites scientific experimentation by mechanisation and reusable components, e.g., protocols. The more scientific experimentation can be expedited, the more new and reliable pieces of evidence could be obtained to facilitate the formulation and testing of scientific theories. Computational synthesis can mechanise the synthesis process and gain higher efficiency. With computational synthesis, scientists may reuse parts of other experiment setups to simplify the task.

1.2.1.2 Better Reproducibility

To provide reliable evidence, experiments must be reproducible in material realisation, experimental process, and results. Tedious and error-prone tasks in material realisation and experimental process would make the experimental results less reproducible. As a technique for mechanisation, computational synthesis is an attractive, though little understood, solution to preparing materials and conducting experiments.

Reproducibility is crucial in scientific experimentation as it is the basis for objectivity (non-biasedness), reliability, and generalisability of the findings from experiments. We tend to believe that our findings are objective if they constantly appear in reproducible experiments; thus, reproducibility of experiments is regarded as evidence for objectiveness. We tend to rule out the possibility that our findings appear just by chance if they constantly appear in reproducible experiments; thus, reproducibility of experiments is regarded as evidence for reliability. We tend to conclude that our findings are generalisable in a group/category if they constantly appear in the same way in reproducible experiments on different members of the group; thus, reproducibility of experiments is regarded as evidence for generalisability.

1.2.2 Synthesis from Experiment Protocols

Experiment synthesis is a knowledge-intensive task. Computational synthesis of experiments should acquire as much knowledge as is appropriate to make the task effective and efficient. On many occasions scientists try to use a component-based approach to synthesising experiments. Experiment protocols can be viewed as forms of specification components that can be not only described declaratively but also encoded in some materials and instruments. Materials for experiments are prepared according to experiment protocols. Instruments for experiment protocols are prepared and operated according to experiment protocols. Materials and instruments are often engineered into commercial products for use with specific experiment protocols. Methods for experiments are then obviously the experiment protocols of interest.

In our computational synthesis, an experiment protocol is basically a specification for a single experiment or one of its components including objectives, specimens (samples), materials, and methods, etc. This is analogous to a declarative specification for a logic program or one of its components including functions, inputs, constants and variables, constraints and axioms, etc. Also analogously to structured refinement is design of declarative specifications, when a single experiment protocol is composed of many smaller experiment protocols, the smaller protocols may be substituted by alternative functionally equivalent protocols to supply a similar contribution to the experiment.

1.2.3 Synthesis of Experiments

An hypothesis supported by this thesis is that in some significantly complex experiments, it is natural to use logic programming in synthesising experiments because of the analogy between experiment protocols and declarative specifications of software components in logic programming. Modular experiment protocols in the form of knowledge components can be used to construct experiments by structural synthesis.

Knowledge representation is required for experiment synthesis. The knowledge representation can specify processes, functions, structures, and components, etc. in protocols. We developed a grammar rule syntax for declarative specifications of the protocols. These protocols are then used to generate generic experiments (e.g., stimuli-response experiments), instruments (e.g., questionnaires, Websites), and domain-specific information (e.g., aviation accident reports). Refinement of an experiment design is achieved when a knowledge component is rewritten (mapped, reduced, bridged, or refined) to other knowledge components using grammar rules. These grammar rules represent the design decisions of scientists. If we have a complete set of grammar rules for the experimental domain, rewriting terminates in a set of materials and setup of the target experiment.

1.3 Exploring Experiment Synthesis

Roughly speaking, there are several kinds of environment for conducting scientific experiments, including those for conducting experiments on computer (*in silico*), in laboratory apparatus (*in vitro*), and in the living organisms (*in vivo*). Pure computational experiments are relatively easy to control and affordable to reproduce. Clinical and psychology experiments on human subjects are difficult to control and expensive to reproduce.

1.3.1 Pure Computational Experiments

Before and in parallel to this thesis, we did some purely computational experiments in bioinformatics, particularly on DNA language parsing by using multiple sets of knowledge acquired from scientists and machine learning (Leung, 1993). In order to render this work significant for publication in the most prestigious bioinformatics journal (Leung et al., 2001) it was necessary to systematise the experiment setup that enabled us to conduct a series of new experiments. The systematisation was done by using specialised gene grammars, which are basically modular experimental setups and easily recombined hypotheses. The significance of this work was due to the discovery of new combinations of knowledge that yielded surprising parsing results. It inspired similar designs for DNA microarray experiments (Leung et al., 2004) These computational experiments motivated us to synthesise more difficult experiments, i.e., cognitive science experiments, as presented in this thesis.

1.3.2 Web-based Experiments in Cognitive Science

This thesis is about the synthesis of Web-based experiments, which use Websites as the material and/or instruments for scientific experimentation involving human subjects. Experiments with human subjects are difficult to reproduce especially if compromises must be made in experiment setups, such as convenience sampling rather than random sampling. This issue is common in psychology and cognitive science experiments. We synthesised two new and non-trivial experiments (including causal experiment and correlational experiment) in cognitive science by using material on aviation accident reporting, in order to evaluate the feasibility of experiment synthesis.

The aim of the first experiment was to demonstrate the inter-subject regularity (if any) in causal perception and to test some of the current causal perception theories using a simple psycho-geometrical scale. Causal perception was chosen as an area of study due to its importance as a cognitive basis for science (Hilton, 2002). Causal perception is the ability to perceive and judge causality from co-variation information. Experimental results from different laboratories have given rise to alternative computational theories proposed by corresponding groups of researchers. These causal perception theories have not been tested in third party (impartial) laboratories like ours. Our experiment findings also have practical application in improving causality information presentation for aviation accident reporting. As the aviation accident reports basically convey information about the causes of aviation accidents, we have to know whether different ways of presenting information (so-called rhetorics) would lead the audience to having different perceptions of the causes of aviation accidents.

The second experiment reused some of the experiment setups of the first experiment. It aims to discover possible correlation (regularity) between design preferences and specific cognitive factors, particularly visualisation ability and analogy-making ability. Better knowledge about this correlation might improve the design of aviation accident reporting Websites for target users, who may be diverse in their preferences and cognitive abilities.

Our broader aim is that these two synthesised experiments for improving aviation accident reporting on the Web may be suggestive of broader use of experiment synthesis in more general domains that require experimentation, including human-computer interaction, software engineering, and cognitive science.

1.4 Scope of the Work

The main objective of this thesis is to develop a set of basic grammars representing experiment protocols for Web-based experiments; to synthesise non-trivial experiments by using the grammars; and to conduct the synthesised experiments in order to obtain scientific findings. The experiment protocols include the specification of experiment material and apparatus, i.e., Websites.

More specifically, the objectives of this work are listed as follows:

- To expedite scientific experimentation by computational synthesis;
- To develop the idea of grammars as a possible knowledge representation for specifying experiment protocols;
- To synthesise Web-based experiments using these grammars;
- To conduct corresponding semi-synthetic cognitive science experiments; and
- To test established causal perception theories and correlation between design preferences and cognitive factors by these semi-synthetic experiments.

This thesis does not cover the (1) controversies in philosophy of science, including causal attribution, (2) creative processes in scientific experimentation such as hypothesis generation, (3) broad statistical issues such as statistical experiment design and data analysis, (4) broader organisational issues such as workflows and dataflows for laboratory management, and (5) technical issues specific only for local research laboratory practices such as the choice of specific hardware.

1.5 Computing Environment

The present work was mainly done under the following computing environment:

- Computer languages: Prolog (SICStus-Prolog[2] and CIAO-Prolog[3]), Perl[4], PHP[5], Javascript[6]
- Operating system: RedHat / Fedora Linux[7]
- Web browsers: Mozilla and Firefox[8]
- Text: LaTeX[9], OpenOffice[10]
- Ontology editor: Protege 2000[11]
- Graphics: Graphviz[12], GIMP[13]
- Statistics: R[14]

1.6 Organisation of this Thesis

This chapter outlined the main motivation and scope of the present study. The following chapters will describe the background, specification, mechanism, and scientific cases for scientific experimentation by computational synthesis.

1. **Introduction**
   This is the present chapter, describing the motivation of the thesis in facilitating scientific experimentation by computational synthesis.

[2] `http://www.sics.se/isl/sicstuswww/site/index.html`
[3] `http://www.clip.dia.fi.upm.es/Software/Ciao`
[4] `http://www.perl.com`
[5] `http://www.php.net`
[6] `http://www.ecma-international.org/publications/standards/Ecma-262.htm`
[7] `http://fedoraproject.org`
[8] `http://www.mozilla.org`
[9] `http://www.latex-project.org`
[10] `http://www.openoffice.org`
[11] `http://protege.stanford.edu`
[12] `http://www.graphviz.org`
[13] `http://www.gimp.org`
[14] `http://www.r-project.org`

2. **Scientific Experimentation**
   This chapter explains some problems of scientific experimentation and potential for computational synthesis to expedite and facilitate experiment setups.

3. **Morganic Grammars**
   This chapter explains a knowledge representation developed for this thesis. It integrates some basic features of frames, typed feature structures, formal concept analysis and conditional rewrite rules in order to transfer the structural knowledge across domains including scientific concepts, experiment concepts, and Website concepts.

4. **Website Synthesis**
   This chapter describes how Website synthesis is done according to a simple Website model.

5. **Experiment Synthesis**
   This chapter describes how computational synthesis is applicable to setting up Web-based experiments.

6. **Synthesised Experiment 1: Causal Perception**
   This chapter reports an experiment synthesised in advance computationally to study causal perception, which is a cognitive basis of scientific investigation.

7. **Synthesised Experiment 2: Preferences and Cognitive Factors**
   This chapter reports an experiment with Website prototypes synthesised on-the-fly to correlate the design preference (individual preference) of the subjects to their cognitive abilities.

8. **Significance and Further Work**
   This chapter summarises the most important and significant findings in the study of this thesis. It also suggests some possible further work to improve the current work to facilitate scientific experimentation and development of Lab-on-the-Web.

Chapter 2

Scientific Experimentation

Scientific experimentation is actively controlled investigation, not passive observation. If possible, all factors affecting the results should ideally be under control by the investigator so that the causal (or covariational) dependence of the results on the particular factors can be shown and evaluated. By contrast, some factors such as the allocation of subjects to treatments in a passive observational study are not controlled by the investigator. Experimentation is probably the most reliable method of doing science. Even though science can be compromised by various flaws, experimentation is still the basic approach to acquiring evidence for scientists to reason about. Experimentation is so important that a theory in science may become obsolete but the reliable experiment from which it was derived may stay to be interpreted by newer theories. The reliability of experimentation is based on the reproducibility of experiments. Reproducibility can be enhanced by protocol specifications, which opens a possibility for using computational techniques to synthesise parts of experiment setups. This chapter will briefly describe certain aspects of scientific experimentation as the domain background of this thesis, particularly the use of protocol specifications in improving reproducibility of experiments and computational synthesis of experiments.

2.1 Anything Goes but Experimentation

As experimentation aims to study regular covariations, possibly causality, it is being used not only in pure sciences. Experimentation has been increasingly used in other fields of research, e.g., artificial intelligence (Gillies, 1996), experimental software engineering (Basili et al., 1999; Shull et al., 2004; Do et al., 2005), experimental mathematics (Borwein and Bailey, 2003), experimental economics (Leonard and Fontaine, 2005), education research (Maxwell, 2004), social experimentation (Campbell and Russo, 1999), and experimental marketing science (Patzer, 1996). Hence, experimentation as a scientific method is crucial to many fields of rigorous research.

A traditional experimentation approach (Coolican, 1990), as advocated by Francis Bacon, is based on inductive reasoning about data and comprises the following tasks:

- observation and data collection;
- hypothesis generation (or theory revision) to explain observation;
- experiments to test hypotheses;
- formulation of a theory;
- testing of this theory; and
- prediction by using the theory.

David Hume[1] suggested a regularity view of causation comprising three criteria for judging causality:

- **Spatiotemporal Contiguity**
  The cause and the effect are adjacent in time and space.
- **Temporal Priority**
  The cause happens before the effect.
- **Necessary Connection**
  There must be a conjoint perception between cause and effect for grounding causal inference, e.g., observing constant conjunction and covariation.

To improve causal induction from observation, John Stuart Mill[2] proposed specific methods of verification, namely the methods of (1) difference, (2) agreement, (3) difference and agreement, (4) concomitant variation, and (5) residues.

[1] `http://www.etext.leeds.ac.uk/hume/ehu/ehupbsb.htm`
[2] `http://www.la.utexas.edu/research/poltheory/mill/sol`

Suppose we have a list of factors (candidate causes) found in one case where an effect occurs and not found in another case where no such effect occurs.

- **Method of difference**
  If the only difference is the presence of a single factor in the cases where the effect occurs, we can hypothesise that this factor would be the cause of the effect.

- **Method of agreement**
  If there is a single factor in all cases where the effect occurs, we can hypothesise that this factor would be the cause of the effect.

- **Method of difference and agreement**
  If methods of difference and agreement are applicable, then we can hypothesise that this factor would be the cause of the effect.

- **Method of concomitant variation**
  If we find a certain property of the effect covariates with a factor common to the cases where the effect occurs, we can hypothesise that this factor would be a cause of the effect.

- **Method of residues**
  If all factors except a specific factor are believed to be the causes for all the effects except one specific effect, then we can hypothesise that this exceptional factor would be the cause of this exceptional effect.

Mill's methods are applicable to causal attribution, the nature of which remains to be ascertained, for experiments and observations (White, 2000). They have inspired many cognitive models of causal induction (Hilton, 2002). Recent cognitive models (Penn and Povinelli, 2007) are probabilistic forms of Mill's methods. These models are formulated using a contingency table (Figure 2.1), in which there are four cells to show the conditional probability data of occurrence (e^+) and non-occurrence (e^-) of event (effect) e under the presence (c^+) and absence (c^-) of a certain condition (cause) c. Like other scientific hypotheses, these models are subject to experimental research. As yet, there is no consensus among different laboratories about these models based on the same tabular formulation

	e^+	e^-
c^+	$P(e^+ \mid c^+)$	$P(e^- \mid c^+)$
c^-	$P(e^+ \mid c^-)$	$P(e^- \mid c^-)$

Figure 2.1: Causal perception from a contingency table

and no third party experimental results obtained by an independent laboratory. Hence, we tested them in a synthetic experiment (Chapter 6).

Experimentation manipulates conditions (intervention) so that we can evaluate the causal relationship between the c and e. Experimentation aims to ensure that:

- (1) the change of c (or its value) is entirely due to the intervention, and
- (2) the intervention changes e (or its value), if at all, only through changing c (or its value).

Condition (1) makes sure that the change of c does not have other causes (other than the intervention). The condition (2) makes sure that the change of e does not have the causes other than the change of c (and its possible effects) (Woodward, 2003).

Being human and humble (and criticised by David Hume), induction is no longer thought to be absolutely reliable. From limited evidence, only experimental falsification of hypotheses is possible and experimental confirmation is impossible (Popper, 1959). Nevertheless, as science is often interested in studying a general category of objects, not individual objects, we have to use inductive inference to generate hypotheses and admit the not-yet-falsified hypotheses as tentative theories, which may later be revised or overruled. To improve reliability in inferring the target category of subjects (population), statistical sampling techniques were introduced to improve the inductive approach. Randomisation of treatment application to subjects was introduced to avoid bias in experiment design.

There are non-technological concerns about the reliability of scientific methods. Scientific research cannot escape from the distortion by social interactions (Barnes et al., 1996) among scientists and other people in the society. Experimentation can be biased by research paradigms, research programmes, and research traditions. Even though new theories appear and looks better, paradigm shifts (Kuhn, 1962) would be difficult without crisis of the old paradigm to motivate scientists to consider a radical change. A research programme supporting a set of theories is interacting (or even fighting) with other research programmes. When a single theory is defeated, the whole research programme will be desperate to try to remedy, e.g., by replacing that single theory with a stronger one (Lakatos, 1977). Research traditions are even more resistant because research programmes can be removed while the research traditions remain (Laudan, 1978). To an extreme, one would even think that anything goes (Feyerabend, 1978) and there seems no reliable scientific method. Experiments and their instruments are constructed according to theories; thus, the experiments are theory-laden and would not be absolutely objective. These are negative views about science. We positively think that scientists need to understand the limits of current scientific methods, but they have to use their best-so-far scientific method, i.e., experimentation, as the last resort. Science still makes progress by rigorous experimentation.

2.2 Reproducibility of Experiments

Pragmatic and naturalistic research into scientific experimentation itself is being revived by philosophical (Haack, 2004; Godfrey-Smith, 2003) and informatics efforts (e.g., eScience). Despite all the previously mentioned theoretical difficulties, we take the view that reproducibility of experiments is a basis (or manifestation) of credibility, reliability, objectivity (non-biasedness or inter-subjectivity) and generalisability. As mentioned, even if a theory fails, its experimental evidence remains there to support (or to be explained by) new theories. It is highly desirable that experiments may be reproduced (with revisions if required) under these new theories. Reproducibility could be demonstrated in repeated, related, similar, or more remotely analogous domains by modified experiment setups. All relevant or reproducible experiments provide evidence to solve the puzzles in science, much like the clues or constraints for crossword puzzles (Haack, 1995, 2004). However, experimentation is never easy. And a growing issue for technology is the extent to which it can make experimentation easier and/or offer new insights of experimental research. A cornerstone of any such effort is reproducibility. We will elaborate a little about the importance of reproducibility of experiments and describe later the use of experiment protocols to enable reproducibility.

2.2.1 Kinds of Reproducibility

There are three kinds of reproducibility in scientific experimentation (Radder, 2003):

- material reproducibility,
- process reproducibility, and
- result reproducibility (or replicability).

All three kinds of reproducibility indicate the reliability of the experiments. Material reproducibility is about whether the materials and instruments for the experiments can be reproduced. Process reproducibility is about whether the procedures can be repeated properly. Result reproducibility is about whether the same results can be obtained when the experiments have been properly done.

2.2.2 Reproducibility Indicates Reliability

Reproducible materials and processes are crucial to achieve result reproducibility. Reproducibility of experiments (results) has been regarded as a substitute for some idealised features of scientific experimentation, including objectivity and generalisability. We cannot guarantee that experiments reflect reality, regardless of how convincing the experiments look. However, reproducibility of experiments gives circumstantial evidence that reality (if any) is being repeatedly found by experiments. Consistent repeated findings according to a theory may help scientists to formulate or modify a theory (Fugelsang et al., 2004). Due to the problem of induction, we are not sure whether we can generalise the experiment results (with limited study cases) to represent the whole category (population). Reproducibility of experiments, however, would increase our confidence that the experiment results are generalisable to represent a category to which the studied cases belong.

Scientists may need to repeat experiments under different contexts. Some may just examine the experimental setups and procedures and they can ensure whether the experiments are credible and reliable. They may repeat the experiments in a slightly or very different context by using similar setups and procedures.

2.3 Reproducibility Through Protocols

Reproducibility needs experiment protocols. These are well-formed experiment instructions (or recipes) as specifications for conducting experiments (Sahdra and Thagard, 2003). They provide details for the scientists in the field to understand and conduct (or reproduce) the experiments. Experiment protocols can exist in the form of instructions and/or be encoded in instruments/apparatus, which can be used by different scientists in different laboratories to (re)produce the results. Protocol 1 shows a typical experiment protocol. In addition to its appearance resembling computer program specifications with variables and procedures, we describe some features of experiment protocols which would make computational synthesis of experiments possible.

2.3.1 Protocols for Specifications

Conventional protocols are sharable experiment documentation, e.g., Current Protocols[3] and Cold Spring Harbor Protocols[4]. The documentation may be in the form of laboratory manuals, sheets of procedures and technical notes. They are the concise but adequate specification for how to carry out the experiments using the required materials, instruments, treatments, data analysis, and/or even result interpretation guidelines. They are used for standardisation of practices and knowledge sharing. However, experiment protocols may not express adequate knowledge for conducting the experiments and thus are difficult to transfer from

[3] `http://www3.interscience.wiley.com/browse/?type=CURRENT_PROTOCOL`
[4] `http://www.cshprotocols.org`

Protocol 1 TCA Precipitation

Materials

- Protein sample solution
- 60% (v/v) trichloroacetic acid (TCA) solution
- Acetone
- Resuspension buffer
- Refrigerated centrifuge
- Ice-bath

Methods

- Place the protein sample solution and 60% (v/v) TCA solution on ice-bath for 20 minutes
- Mix four volumes of protein sample solution with one volume TCA solution
- Leave on ice-bath for 120 minutes
- Centrifuge at 4000g or more in a refrigerated centrifuge for 15 minutes
- Wash using acetone
- Resuspend the precipitate in resuspension buffer

one laboratory to another (Shull et al., 2002; Sahdra and Thagard, 2003).

Protocol 1 is a simple experiment protocol to retrieve proteins by denaturing and precipitating with strong acids. Most biologists can understand and carry out the experiment procedure according to the protocol. However, this protocol would not make sense to many other people who did not study biology in the laboratory. Even though it is the ideal for the protocol to enable one to reproduce the experiment autonomously, this domain-specific protocol demonstrates that experiment protocols as specifications may not provide sufficient information for conducting the experiments. General background knowledge and local laboratory knowledge are required. It is no wonder that technology transfer between laboratories is often required to ensure reproducibility. As materials are often the basis of process and result reproducibility, materials are sometimes shared in the process of technology transfer to achieve better reproducibility (Lange, 2003). If standardised materials such as experiment toolkits and instruments are used, the reproducibility may need less time and effort to achieve. It is also preferable to develop parameterisable experiment protocols to enable computational synthesis and to minimise human intervention and human influence.

2.3.2 Protocols for Material Reproducibility

Experiment protocols can be encoded in some reusable materials or instruments (e.g., showcards, data collection forms, and software) for material realisation of the experiments. For instance, there is a cognitive factors testing toolkit including instructions, showcards, and data collection forms (French et al., 1963). We used this toolkit in our experiment on design preference (Chapter 7). New experiments can be easier to plan using reusable protocols. In addition to the reusable paper-based toolkit, we also reused the Website synthesiser, which was used as an instrument in our causal perception experiment (Chapter 6), to generate synthetic Web material for a Web-based experiment. In recent years, the Web is also used to conduct simple canned experiments, e.g., the teaching laboratory packages for cognitive science (Mizuno, 2004). These are supposed to run teaching experiments repeatedly without modification. It is desirable to automate the preparation of experiments. However, few methods exist for automated and flexible generation of Web-based experiments, let alone the computational synthesis using parameterisable experiment protocols based on knowledge representation formalisms.

2.4 Experiment Synthesis Through Protocols

To plan an experiment, we need to determine the study variables of our hypotheses, target population and samples (subjects or experimental units), treatments, statistical experiment design, measurements, data analysis, and reporting. Each of these could be specified in experiment protocols for proper conduct, reduction of biases/errors, and higher reproducibility (Ioannidis, 2005). A simplified model of experimentation is described as follows. We formulate our hypotheses based on research questions. We determine the study variables in our hypotheses, e.g., independent variables (causes), dependent variables (effects). We formulate various kinds of treatments based on the study variables. The materials, instruments, and methods for the treatments should be specified. To avoid bias and errors, we determine our target population and statistical sampling method to select experiment units. We also carry out [statistical] experiment design. Suppose there are n given experimental units, and v treatments. One treatment is applied to each experimental unit as specified by the scientists, and then one response Y is measured on each unit. The data collected from measurements will be subject to analysis and reporting. If all these experiment elements can be specified in protocols, experiment planning would be much easier.

2.5 Towards Lab-on-the-Web

To reduce human errors and increase reproducibility of experiment process, highly automated instruments are desirable. For example, Lab-on-a-Chip[5] incorporates all reagents and processes to conduct experiments. Experimenters need only to input the experiment parameters (conditions) and apply the samples to the chip. The chip is processed by a computerised instrument to carry out all required experimental steps. The results can then be read or printed from the instruments for further use. It is easy to make an analogy between Lab-on-a-Chip and the Web. We are hoping to develop some Web-based instruments to conduct experiments by the Web, i.e., Lab-on-the-Web.

As Web-based experiments are usually done by subjects rather than experimenters, the materials provided to the subjects are basically the Websites, which constitute a major portion of the experiment. For Web-based experiments, computational synthesis mainly synthesises the Websites as the experiment materials in a way suitable for experimental purposes. As material reproducibility supports other kinds of reproducibility, the material synthesis of Web-based experiment should improve their reproducibility. Computational synthesis would have the following advantages for supporting a future Lab-on-the-Web:

- It synthesises the experiment materials, including instruments;
- It incorporates process into instruments, which will become material; and
- It expedites and facilitates systematic experiments.

[5]`http://www.rsc.org/Publishing/Journals/lc`

From another point of view, most of the materials need to be synthesised for Lab-on-the-Web. It is difficult to find a single tool to synthesise so many different materials. We therefore need a wide-spectrum language for knowledge representation in experiment synthesis. The next chapter will describe our language developed for representing this form of diverse knowledge.

2.6 Chapter Summary

Normally the major criticisms of sciences are on the scientific theories rather than experimentation, which remains the most reliable methodology to produce scientific evidence. New theories should explain old evidence. Experimentation is methodical and often specified in experiment protocols for communication among scientists. Hence, reproducibility of experiments can be improved through re-use of rigorous protocols. For reusability, experiment protocols must be made modular. This view of experiment protocols leads to our research into experiment synthesis. The rigour needed to make synthesis possible (even partially in an automated way) also makes reproducibility possible with minimal human intervention.

Chapter 3

Morganic Grammars

Scientific experimentation tests hypotheses in science by using more definite/reliable knowledge. This kind of knowledge needs language for its representation. For computational synthesis of experiments, natural language is still difficult for computers to process. On the other hand, computational logics are still difficult for most scientists to grasp. Our ideal knowledge representation is scientifically significant, technically simple, and practically useful to users, including knowledge engineers and end users. Scientific significance of knowledge representation helps mirror the target knowledge. Technical simplicity of knowledge representation enables the users to focus on the knowledge rather than the technical representation. Practical utility of knowledge representation fulfils the design goals. This chapter describes our knowledge representation, called morganic grammars, aiming to provide these advantages. Our use of morganic grammars for computational synthesis is described in later chapters.

3.1 Cognitive Schemas and Grammars

Concepts are structural units of knowledge (Jin, 1983). Their patterns/constructs for various cognitive activities are called schemas. The term schemas was used by Aristotle to describe valid syllogism patterns. It was also used to describe the rules that can accommodate all possible aspects of a concept (Kant, 1787). It was introduced around 1932 by Frederic Bartlett to experimental psychology to describe the units of internal knowledge representation of a domain of interaction between internal and external worlds (Bartlett, 1995). Since then, in cognitive psychology, schemas have been thought to be generalised representations of overall total situations (Neisser, 1976) as well as informative representations to enable an agent to act in a coordinated manner over a whole range of analogous situations (Piaget, 1971). In later cognitive science and artificial intelligence studies, schemas are treated as a set of inference operations for thinking (Holyoak and Spellman, 1993), information processing (Hunt, 1989), deductive inference (Falmagne and Gonsalves, 1995), pragmatic reasoning (Cheng and Holyoak, 1985) using causal and regulation schemas (Holyoak and Spellman, 1993), as well as interpretative patterns of existing knowledge for acquiring new knowledge (Gallagher, 2004). Despite the fact that schemas are commonplace in cognitive psychology experiments, there is no generally agreed computational representation of schemas. In some cases, they are expressed as production rules (Cheng and Holyoak, 1985). In other cases, they are treated as a version of predicate calculus (McDermott, 1987) that is simply equivalent to the early work of Marvin Minsky on frames (Minsky, 1975). So far, they are still regarded as a more flexible alternative to mental models and mental logics in explaining about human reasoning (Holyoak and Morrison, 2005). Specific reasoning schemas include causal schemas (e.g., prediction, diagnosis, and explanation), regulation schemas (e.g., permission, obligation), spatial schemas (e.g., geometry, graph). It is believed that schemas can be translated from the corresponding natural language representation and can be translated into their corresponding logics, e.g., obligation schemas being translated into denotic logic (Falmagne and Gonsalves, 1995). Our preference for using schemas over natural language and logics are due to the fact that schemas are effective ways of representing standard forms of human reasoning but less complicated than natural languages (Jurafsky and Martin, 2003) for computation and less cryptic than more deeply mathematical languages such as modal logics (Blackburn et al., 2006) to non-logicians.

In searching for the fundamental representation of schemas for computation, theoretical and practical reasons motivated us to use grammars in representing schemas. Particularly, we found rewrite rules representing grammars quite suitable. A rewrite rule as follows:

$$\varphi \to \psi$$

indicates that whenever we encounter the element φ, which is to the left of the arrow $\rightarrow$, we can replace it by the element ψ.

Grammars are a schema-like abstraction of language patterns, which can be coarse-grained to represent overall situations or fine-grained to represent detailed mechanisms. Some linguists and cognitive scientists believe that some grammars, i.e., universal grammars, are sharable by all languages (Chomsky, 1980; Smith, 1999) and the language faculty might be [partially] in common with other cognitive abilities (Boeckx, 2006). We do not know whether there are universal reasoning schemas but grammar rules should be easier to understand than modal logics. Considering the knowledge we want to represent, the syntax of grammars is preferable to that of modal logics. We use it in computational synthesis of Websites (Chapter 4) and experiments (Chapter 5).

3.2 Integrating Knowledge Representations

Besides grammar rule syntax, we will also need some other features to represent the properties or parameters of the concepts of interest. For example, we need to represent concepts and their properties, to organise and reason about the concepts according to their hierarchical relations. Thus, frames, typed feature structures, frame-based ontology languages, formal concepts (in formal concept analysis) are relevant to the syntax development of the grammars we need.

3.2.1 Frames

A frame is a data structure as a network of nodes and relations for representing a stereotyped situation (Minsky, 1975; Sowa, 2000; Brachman and Levesque, 2003). It was inspired by Bartlett's idea of schemas (Minsky, 1975). Schematically in LISP-like syntax, a frame looks like this:

```
(frame-name
        <slot-name1   filler1>
        <slot-name2   filler2>
        ...
)
```

The frame and slot names are atomic symbols; the fillers can be atomic values (e.g., numbers or text strings) or the names of other frames. There are two types of frames, individual frames describe instances of generic frames which include information about a concept hierarchy. Their specific difference in notations, e.g., INSTANCE-OF slot for individual frames and IS-A slots for generic frames, can be found in various AI texts (Brachman and Levesque, 2003). Reasoning about the relations among frames normally is done with the slots INSTANCE-OF and IS-A and their filler values.

3.2.2 Typed Feature Structures

Typed feature structures (TFS) use attribute-value matrices (AVM) to specify features of linguistic categories for possible conceptual inheritance reasoning using a type hierarchy (Carpenter, 1992). The type hierarchy is basically a finite partial order $\langle \mathit{Type}, \sqsubseteq \rangle$. The following is an example of the AVM syntax of typed feature structures.

$$\begin{array}{c}\textbf{sentence}\\ \begin{bmatrix} \mathit{SUBJECT}: & \mathit{noun} \\ & \begin{bmatrix} \mathit{AGREEMENT}: & \mathit{syn} \\ & \begin{bmatrix} \mathit{PERSON}: X \\ \mathit{NUMBER}: Y \end{bmatrix} \end{bmatrix} \\ \mathit{PREDICATE}: & \mathit{verb} \\ & \begin{bmatrix} \mathit{AGREEMENT}: & \mathit{syn} \\ & \begin{bmatrix} \mathit{PERSON}: X \\ \mathit{NUMBER}: Y \end{bmatrix} \end{bmatrix} \end{bmatrix}\end{array}$$

In this notation, each bracketed entry represents a node and the type of node is indicated at the top of the node. The slots are the features and their values are written next to them. As indicated in this example, the values of the features PERSON and NUMBER should have same corresponding values (X and Y) for agreement. As AVMs can be nested, typed feature structures can be used to implement grammars for natural language processing (Copestake, 2002).

	Frames	TFS	FCA
Object	Frame	Type	Object
Properties	Slot	Feature	Attribute
Values	Filler	Value	Value
Form	List	AVM	Cross-table

Figure 3.1: Comparison of Frames, TFS, and FCA

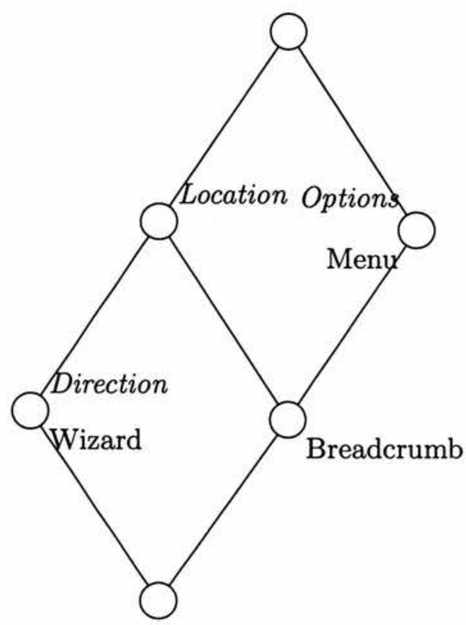
3.2.3 Formal Concept Analysis

Formal concept analysis (FCA) is a mathematical formalism which formulates concepts as "objects and attributes" (Ganter and Willie, 1999), similar to a frame system's "frames and slots" and typed feature structures' "types and features". The objects and attributes are usually represented by cross-tables. Their characteristics can be compared with those of frames and TFS (Figure 3.1).

FCA also has concept lattices to serve roles similar to a type/frame hierarchy in other formalisms. Algorithms were developed for generating the FCA lattice. Figure 3.2 shows an example of a concept lattice generated from a cross-table of objects and attributes. The attributes of a specific object can be computed by collecting all attributes located along ascending line paths from the object. The objects having a particular attribute can be computed by collecting all objects reachable through descending line paths from the attribute. We would like to incorporate this simple representation into our grammars so that we can do some concept data analysis (Carpineto and Romano, 2004) when necessary.

3.3 Morganic Grammars

There are different types of grammar rules to provide sufficient flexibility as knowledge representation requires (Chomsky, 1980). Grammars can be used to represent the knowledge other than natural languages. For example, nucleic acids such as DNA (Leung et al., 2001) can be represented by grammars. Grammars can be easily maintained as they are modularly and incrementally developed. In



Navigation Tools	Location	Direction	Options
Menu			×
Breadcrumb	×		×
Wizard	×	×	

Figure 3.2: Concept lattice and cross-table.

addition, we would like to keep our grammars as simple as possible. Even if the domain experts do not like to deal with technical details in representations, they can still learn simple grammar quickly. Domain experts can then work with knowledge engineers and professional programmers to refine the coarse-grained simple grammars into the required syntax. Grammars allow us to adopt readily available parameterised knowledge components after specifying those external components using grammatical categories.

3.3.1 Morgans are Grammatical Categories

In morganic grammars, each morgan is composed of one or more atomic and/or composite morgans. Thus, a morgan can be as simple as an atom or a huge compositional object. The term morgan (or m-organ) is after the notions of modules and organs, especially mental organs (Chomsky, 1980). The prefix m- denotes morphism or mutation. The root name organ is also known in classics, e.g., Organon by Aristotle and Novum Organum by Francis Bacon.

A morgan has attributes representing its properties. Such attributes are useful to specify some parameters of the morgan. Among morgans, there are carriers. Carriers are responsible for relating or connecting morgans by reductive or transductive morphisms. Thus, carriers may be thought to be conceptual glue (glia), e.g., channels, axioms, conditions, constraints, evidence, preference, explanation, justification, transporters, catalysts, depending upon specific requirements for conception. Morphisms among morgans are specified by grammar rewrite rules.

Morganic grammars specify how morgans were put together by carriers and form our representation for conceptual schemas. In our practical applications, this knowledge representation facilitates the synthesis of Websites and materials for scientific experimentation.

3.3.2 Definition of Morganic Grammars

The grammars can be described formally. A grammar Γ is denoted by a tuple $\langle A, M, R, S \rangle$ which consists of a finite set of atomic morgans A, a finite set of composite morgans M, a finite set of grammar rules R, and a finite set of starting morgans S as the objects of computational synthesis such that $A \cap M = \phi$ and

$S \subset M$. A grammar rule $r \in R$ is a relation in $(A \cup M)^*$ of the form

$$m \xrightarrow{C} m'$$

where $^+$ means one or more, * means zero or more, $m \in (A \cup M)^+$, $m' \in (A \cup M)^*$, and C is a set of optional carriers under which the grammar rule is applicable. m, m', and C can contain optional attributes and values. At least one grammar rule has s as the LHS. The language of a grammar $L(\Gamma)$ is composed of all morgans that may be derived from an s.

3.3.3 Attribute Structures of Morgans

Attributes (or features) can be introduced into morgans. The morganic attributes can be specified as the ordinary arguments or parameters, e.g.,

$$m(v_1, v_2, ..., v_n)$$

where $v_1, v_2, ..., v_n$ are the values of the attributes assigned to specific positions of the parameters of the morgan m. We found this kind of simple attribute structure useful in our applications. However, this way of encoding can be inconvenient for complicated cases in which only a small subset of numerous attributes are required and/or the attribute structure is hierarchical. In such cases, one may prefer using attribute value matrices, i.e., bracketed pairs of attributes and values. An attribute value matrix of a morgan is shown as follows:

$$\begin{array}{c}\textbf{webelement}\\ \begin{bmatrix} attr_1 : & x \\ & \begin{bmatrix} y_1 : z_1 \\ y_2 : z_2 \end{bmatrix} \\ attr_2 : val_2 & \\ \ldots & \\ attr_n : val_n & \end{bmatrix}\end{array}$$

This attribute value matrix describes a Web element (*webelement*). The symbol : is placed in between each attribute name (e.g., $attr_2$) and its corresponding value (e.g., val_2). The attribute $attr_1$ have sub-attributes which are provided in an attribute value matrix.

3.3.4 Morganic Grammar Rules

Morganic grammar rules (MGR) can be written schematically as follows:

$$
\begin{array}{|l}
m \rightarrow m_1, m_2, ..., m_n \\
\hline
C
\end{array}
$$

where m represents the source morgan, $m_1, m_2, ..., m_n$ represents a sequence of target morgans, C represents a set of the optional carriers, and the symbol $\vdash$ serves as a delimiter to separate morgans and carriers. The rewrite $m \rightarrow m_1, m_2, ..., m_n$ on the upper part of $\vdash$ specifies the rewriting of source morgan m into target morgans $m_1, m_2, ..., m_n$ is allowable provided that the optional carriers C in the lower part of $\vdash$ are satisfiable. There are logical connectives between carriers in C.

As morgans can have attributes, the carriers $c_1, c_2, ..., c_k$ can specify the relations of the attributes between source and target morgans in the same MGR.

$$
\begin{array}{|l}
\begin{array}{ccccc}
\textit{webpage} & \rightarrow & \textit{menu} & \textit{content} & \textit{navbar} \\
\left[\begin{array}{ll}
attr_1 : & x \\
 & \left[\begin{array}{l} y_1 : z_1 \\ y_2 : z_2 \end{array}\right] \\
attr_2 : valpg_2 & \\
... & \\
attr_n : valpg_n &
\end{array}\right]
& &
\left[\begin{array}{l}
attr_1 : valpm_1 \\
attr_2 : valpm_2 \\
... \\
attr_n : valpm_n
\end{array}\right]
&
\left[\begin{array}{l}
attr_1 : valpc_1 \\
attr_2 : valpc_2 \\
... \\
attr_n : valpc_n
\end{array}\right]
&
\left[\begin{array}{l}
attr_1 : valnb_1 \\
attr_2 : valnb_2 \\
... \\
attr_n : valnb_n
\end{array}\right]
\end{array} \\
\hline
\bigwedge_{i \in N} \textit{compatible}(attr_i, [valpg_i, valpm_i, valpc_i, valnb_i])
\end{array}
$$

The unification m_1 and m_2 of two morgans m_1 and m_2 is the greatest lower bound of m_1 and m_2 in the collection of morgans ordered by subsumption (hierarchy). Simple unification algorithms are available (Gazdar and Mellish, 1989) for attribute-value matrices. The comprehensive algorithm for unification and subsumption of typed feature structures is available in the Attribute Logic Engine (ALE)[1]. At the moment, our implementation only supports unification.

[1] `http://www.cs.toronto.edu/g̃penn/ale.html`

3.3.5 Prolog Syntax of Morganic Grammar Rules

Our software tools for handling morganic grammars were implemented in Prolog. We can specify a single grammar rule as follows:

```
% a simple morganic grammar rule
morgan0(X) ---> morgan1(Y), morgan2(Z) :-
     carrier1(X,Y),
     carrier2(X,Z).
```

left-hand-side (LHS) category, an arrow symbol (i.e., `--->`) , one or more right-hand-side (RHS) categories, and optionally a set of carriers preceded by an `:-` symbol. The arrow symbol represents a possible rewriting from the LHS category `morgan0` to the RHS categories `morgan1` and `morgan2`, provided that the carriers `carrier1` and `carrier2` are available and satisfiable. The `:-` operator separates rewrite part and the carrier part. Each grammar rule completes with a full stop (i.e., '.').

3.4 Chapter Summary

This chapter proposes morganic grammars, which aim to integrate some features from other knowledge representation formalisms, as a wide-spectrum language for computational synthesis of Websites and experiments. Morganic grammars have morgans, rewrites, and carriers. Morgans incorporate features from frames, typed feature structures, and formal concepts in formal concept analysis. The rewrites are under the conditions that carriers are available and satisfiable.

Chapter 4

Website Synthesis

Synthesis puts things together to form a new thing for some purpose. For the Lab-on-the-Web, we need to put experimental materials (and instruments) together on the Web for scientific experimentation. As long as the target Websites can be specified, computational synthesis can help generate the target Websites in an automated manner, and make them modifiable and reusable.

Computational synthesis of Websites has been around for a decade for Website construction and maintenance. As early as 1996, formally specified information was being automatically transformed into Websites (Robertson and Agusti, 1999). This type of synthesis uses a specific language and transformation rules to construct non-trivial Websites. The transformation techniques are basically the same as those used in program synthesis, in particular structural synthesis, in which reusable design components are parameterised, configured, and refined to bridge the gap between problem description and final specification (Cavalcanti and Robertson, 2000, 2003).

For scientific experimentation, we found we need a more wide-spectrum language and knowledge representation so that the high-level specifications of Websites and experiments can be written in the same rule syntax. We incorporate a grammar-based knowledge representation (i.e., morganic grammars) explicating a Website design model (our simple Website interface model: SWiM), and conditional rewriting to conduct Website synthesis. We aim to simplify Website synthesis so that ordinary Website designers and programmers would find it more accessible. This chapter describes a possible implementation of Website synthesis suitable for later scientific experimentation.

4.1 Computational Synthesis of Websites

Computational Website synthesis has been developing to facilitates the construction and maintenance of Websites and their components. It helps Web developers and customers cope with technical problems (Leung and Robertson, 2003) such as:

- Short life cycles from continual re-design;
- Diversified customer preferences;
- Frequent content updates; and
- Reliability assurance.

Theoretical and applied research into software engineering has used program synthesis (Lowry and Duran, 1989; Czarnecki and Eisenecker, 2000) to generate customised and optimised intermediates or end-products of software components. The basic idea of synthesis is to incrementally refine a high-level specification until an implementation is derived. If a significant level of automation can be achieved, its advantages are numerous, such as the increase in productivity, cost reduction, guaranteed consistency, and compliance of standards. We do not elaborate on these advantages in this thesis. Successful applications of program synthesis in specific domains are synthesis for ecological models (Robertson et al., 1991) and astrophysics models (Lowry and Van Baalen, 1997). The limitations of program synthesis for general use are mainly due to the fact that the existing technologies are insufficient and/or the acquired domain knowledge is inadequate. To gain an improvement, we still need to develop better techniques and acquire useful domains / task-specific knowledge.

From our point of view, Website synthesis would be useful to the Lab-on-the-Web for at least two reasons:

- the Websites for a single Web-based experiment are often constructed in a regular and standard way to enhance experimental controls; and
- the Websites for an experiment do not usually require a full set of complex interactive features but simple regular structures for experimental manipulation.

Therefore, at this stage of development, we ignore the Websites which do not follow predictable patterns. Such Websites would require custom programming and they can be as complicated as the most sophisticated programs. We focus on those Websites in which design decisions are consistently justifiable by explicit knowledge, i.e., rational Web design. When there are conceptual gaps between knowledge representations, e.g., between information content and Web design components, we need grammar rules for mapping to bridge those gaps. Such grammar rules represent Web design decisions or principles.

There is a search space of rewrites from an initial domain-specific ontology leading to a detailed Website content description. In simple cases, where there is exactly one route through this space, we have a fully automatic synthesis procedure. If there are multiple routes leading to different results, interactions with human or automated reasoners at choice points or additional problem-specific constraints are necessary. The final step transforms the final Web content description into a Website.

4.2 Website Design Model

Website design is highly dependent upon the creativity of individual Website designers. A popular model for Website design was developed by Jesse James Garrett (Garrett, 2003), seeing Website design to have five conceptual planes (layers):

- **Surface Plane**, specifying the visual design, particularly visualisation (surface realisation) into images and text that we can browse and click on;
- **Skeleton Plane**, specifying the information design (the interface from the software aspect including the interface elements to enable interaction with users), and navigation design (the navigation elements to enable users to move in the information architecture);
- **Structure Plane**, specifying the required interaction from the software aspect and information architecture from the information aspect;
- **Scope Plane**, specifying functions (feature sets) from the software aspect and content (information units) from the information aspect; and

- **Strategy Plane**, specifying the strategies to arrange the functions and facilities to meet user needs.

The surface plane is the most concrete one while the strategy plane is the most abstract one in this model. Each plane depends upon the more concrete planes. Design decisions for each plane must be aligned well with those above and below. Plane by plane, the design decisions may become more refined. Although our work was developed before the publication of this Web design model, this model suits our ideas of Website synthesis, which requires mapping among different domains (e.g., planes or layers) by using grammar rewrite rules. The development of these planes can be made interdependent or moderately independent of one another.

4.3 Simple Website Interface Model

Simple Website Interface Model (SWiM) is our specific model for Website synthesis, rather than a general Website design model. Both SWiM and the Garrett's model were developed independently without knowledge of each other's development; thus, any similarity between both models should be due to commonly observed Website design practices. SWiM divides Website synthesis into two major parts, information synthesis and presentation synthesis. SWiM for Website synthesis is roughly equivalent to the structure, skeleton, and surface planes of Garrett's Website design model. Information synthesis is mainly tackling the issues on structure plane. Presentational synthesis is dealing with the problems on skeleton and surface planes. Garrett's model and SWiM share common patterns of tasks in Website design process. However, Garrett's model is supposed to cover all design activities while SWiM is a set of minimal concepts to facilitate the technical construction of Websites by computational synthesis.

The basic approach to synthesis taken in this thesis is to anchor Website synthesis in declarative specifications, preferably in morganic grammars, and supported by various Website components. At the stage of information synthesis, source information in a tree structure is transformed into the content information tree which is suitable for presentation on the target Website. Presentation synthesis comprises navigation synthesis and visualisation synthesis. At the stage of navigation synthesis, the structural features of the content information were identified and extracted to serve as a navigation information tree. In the visualisation synthesis, content information tree and navigation information tree are visualised by using available Website components. We briefly describe the processes of information synthesis, navigation synthesis, and visualisation synthesis in this section and give some examples in later sections.

4.3.1 Structure Refinement

The Website synthesis according to SWiM begins with a given set of information units which is in a tree (or linear) structure. Information units serve as the nodes of the tree. Their hierarchical relationships are represented by links between nodes in the tree. The tree structure provides a clear and definite structural relationship among information units. In addition, it is likely to have weaker relevance among information units that could not be represented in a single tree structure. This weaker relevance can be recorded as pointers for realisation of visualisation as hyperlinks.

In many cases, the information tree would require some trimming and splicing for structure refinement. The refinement is to rearrange the information units into a [different] tree structure so that users may find the information easier to access. A simple heuristic for refinement is to put a reasonable amount of related information in a branch (partition) of the tree. More detailed information can be given in its sub-branches. The information trees for our example Websites are small; thus, no special structural refinement is needed except minor refinement to remove unimportant information units and to group singleton units with other information units.

4.3.2 Navigation Synthesis

To enable structural navigation of the information units, some indexical items should be required to provide an overview of the information trees. For instance, categorical names of some information units would serve as menu items. When a user selects a menu item, he is requesting to see the specific information units under this category. Navigation synthesis is to collect these indexical items in order to visualise them later as the navigation facilities such as menus and navigation bars. The result of navigation synthesis is a navigation tree.

4.3.3 Visualisation Synthesis

Visualisation synthesis realises the information trees and navigation trees as the the Web materials for final presentation. We use the Prolog-to-HTML converter PiLLoW (Cabeza and Hermenegildo, 2001) to generate the final HTML documents. Before we can feed the information and navigation trees to PiLLoW, we need to synthesise the layout of the information units and navigation facilities on the Website. For instance, a simple Web page has a logo, a banner, a menu, a navigation bar, and a content area. These facilities should be positioned (layout) on every Web page. Logos and banners are site elements for identities, branding, and advertising. Menus and navigation bars are navigation elements for overview and selection of the information. Content areas contain actual information units to present to the users.

There are two basic types of elements in SWiM for visualisation synthesis, i.e., tabular cells and unit cells. They form layout grids and place holders (compartments) for individual visual components. Each tabular cell contain zero or more other tabular cells and/or unit cells. Each unit cell can also contain zero or more tabular cells and/or other unit cells. Operationally, visualisation synthesis uses available cells to hold information units and Website components, including text, tables, and/or graphics. For simplicity, a single cell is preferably holding only one information unit or Website component, which unit or component can be atomic or composite.

A single cell is simply a place holder of Website components. It has a cell wall (border) which can be made visible or invisible, thick or thin, and shaded with colour. A table has rectangular cells (m rows by n columns). To take a 3x3 table as an example, in which there are nine cells, we can arbitrarily name the central cell as (1) Centre, and then other cells clockwise from top (2) North, (3) Northeast, (4) East, (5) Southeast, (6) South, (7) Southwest, (8) West, and (9) Northwest. Each cell may contain zero or more other tabular cells and/or other types of cells. Any cell may be fused with neighbouring cells to form bigger cells. The sizes of cells are adjustable although the sizes of the same rows and columns should be consistent. Each non-empty cell should contain Website content or navigational information as well as related Website components for visual presentation. Our implementation uses tabular cell layout. For instance, to represent an ordinary home page in a 3x3 table, the Centre cell contains the content information units. The Northwest cell contains a site logo. The North cell contains a banner. The West cell contains a menu (table of contents) and optionally some other services (e.g., search). The South cell contains a navigation bar. The East cell contains some optional images.

Unit cells under SWiM can be treated like boxes for CSS layout (Griffiths, 2006; Muller, 2007) and layout of multi-column Web pages using CSS stylesheets is feasible[1]. As different browers may behave differently, a recent W3C Working Draft[2] was proposed (dated 6 June, 2007) to provide a multi-column model for page layout using CSS stylesheets. It is expected that multi-column page layout will become easier after standardisation.

4.3.4 Features of SWiM

SWiM is a way of summarising simple practices of Website construction to provide Website synthesis with:

- A plausible conceptual framework to partition tasks among information synthesis, navigation synthesis, and visualisation synthesis, as well as identifying the gaps between them.

- A simple structural framework to organise the information units in tree structures, and to facilitate extraction of indexical features of information units to form navigation (context) trees.

- A layout framework (using tabular cells and unit cells) to organise information units and Website components on Web pages.

SWiM has been useful in our experiment synthesis research where the objective is to build a large number of simple Websites. However, SWiM is not directly applicable to synthesising complicated Websites without specifiable patterns.

[1] `http://yaml.de`
[2] `http://www.w3.org/TR/2007/WD-css3-multicol-20070606`

Protocol 2 Rewriting of Morgans

Require: a set of morgans M
Require: a set of morganic grammar rules
for all $m \in M$ and m is rewritable **do**
  if m is unifiable with the LHS morgan of a grammar rule **then**
    if all carriers (conditions) of the grammar rule are satisfiable **then**
      unify the attributes of the RHS morgans of the grammar rule with the attributes of the LHS morgan and carriers
      add all RHS morgans to M
    end if
  end if
end for
return M

4.4 Rewriting for Website Synthesis

Each grammar rule has a single morgan on the left hand side (LHS), which can be rewritten to the morgans on the right hand side if and only if all carriers (conditions) are satisfiable at the time of rewriting. We can use morganic grammar rules to specify the source information, the synthesis tasks as suggested in SWiM, as well as compatible Website components. The rewrite rule interpreter serves as a Website synthesiser to synthesise Websites. Protocol 2 shows how the synthesis can be generally done with the rewriting of morgans.

The core Prolog code of the rewrite rule interpreter for Website synthesis is listed in Appendix A.

4.5 An Example of Website Synthesis

This section exemplifies how Website synthesis works. To specify an overall Website synthesis, we can specify the initial input (an information tree/list), and final output (a Prolog list of Web elements to be interpreted by PiLLoW for HTML generation). The intermediates between the initial input and final output can be specified in separate grammar rules or treated as expanded carriers of the gramaccidents

case :

case1

eventList :

eventList1

event :

e9

eState : cruise
ePicture : http://websyn.dai.ed.ac.uk/images/lackpower.jpg
eCrypticName : kiodwa
eName : PassengerReport
eDesc : Passengers told flight attendants about sparks from engine A
eAltitude : 1023
eDistance : 13.5
eTime : '19:03:15'
eCauses : e2, e6, e8

...

...

...

Figure 4.1: An example of source information trees

mar rules. In this example, we synthesise a Website to present aviation accidents. Each accident comprises multiple events. The information of aviation accidents is represented in a morgan with an attribute-value matrix (AVM) as shown in Figure 4.1.

Suppose Website synthesis begins with the morgan *source(Info)* and progresses into the navigation synthesis:

$$\frac{source(Info) \rightarrow navigation(InfoTree, NaviTree)}{\begin{array}{l} structureRefinement(Info, InfoTree) \wedge \\ indexFeatures(caseName, 0, InfoTree, NaviTree) \end{array}}$$

where the variable *Info* is instantiated with the AVM in Figure 4.1. The carrier *structureRefinement* extracts the event information including *eName*, *eState*, *caseName*, *ePicture*, *eCauses*, *eDesc* and the consequent event. The consequent event needs computation from the context among events. These pieces of extracted information are stored in the variable *InfoTree*. The carrier *indexFeatures*/4 is responsible for extracting the indexical items from the information tree *InfoTree* and creating a navigation tree *NaviTree*, which is a result of extraction of the attribute *caseName* (and the attributes at the depth of zero level below). The indexical extraction collects the values (i.e., category names) of the hierarchical attributes in the tree. The extraction result $[case1, case2, case3, ...]$ is stored in *NaviTree*.

For visualisation, in addition to *InfoTree* and *NaviTree*, we also need a logo, a banner, a menu, and content information in synthesis of a Web page. The logo and banner are the same across pages and we just need to retrieve them from the given locations as specified in the following grammar rule:

$$\begin{array}{|l}
navigation(InfoTree, NaviTree) \rightarrow \\
visualisation(Title, TitleImage, LogoImage, Cases, Content) \\
\hline
logo(LogoImage) \wedge \\
banner(Title, TitleImage) \wedge \\
cases(NaviTree, Cases) \wedge \\
refinement(InfoTree, Content)
\end{array}$$

The case codes are extracted from *NaviTree*. In this example, tables are used to layout the information of individual events. The information about *eName*, *eState*, *caseName*, *ePicture*, *eCauses*, *eDesc* and the consequence of each event are put into tabular cells. The events of each accident are presented in a single Web page. The result of presenting accident events is stored in *Content*, which is transformed into a Prolog list in compliance with PiLLoW for subsequent conversion into HTML.

$$\begin{array}{|l}
visualisation(Title, TitleImage, LogoImage, Cases, Content) \rightarrow \\
pillowHtml(Dir, SiteContent) \\
\hline
outputDirectory(Dir) \wedge \\
caseList(Cases, Menu) \wedge \\
visualiseSite(Content, Title, TitleImage, LogoImage, Menu, SiteContent)
\end{array}$$

The following predicates are the Prolog code of carrier *visualiseSite* to layout

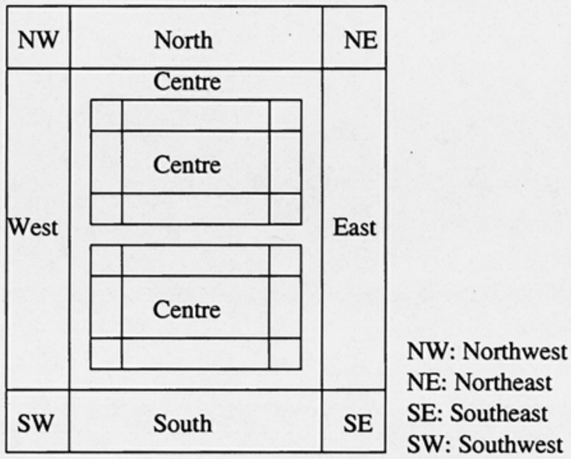


Figure 4.2: A schematic view of tabular cell layout

pages of this simple Website:

```
visualiseSite([], _, _, _, _,[]).
visualiseSite([H|T],Title,TitleImage,LogoImage,MainMenu,
        [PageContent|OtherContent]):-
    visualisePageContent(H,Content),
    visualisePage(Title,TitleImage,LogoImage,MainMenu,Content,PageContent),
    visualiseSite(T,Title,TitleImage,LogoImage,MainMenu,OtherContent).

visualisePage(Title,TitleImage,LogoImage,MainMenu,Content,PageContent):-
    tabularCells(LogoImage,TitleImage, [], [], [], [], [],
        itemize(MainMenu), Content, PageContent).
```

where the arguments of `visualisePage` are to put different pieces of information into tabular cells clockwise starting from Northwest (top left) of a 3x3 table. Multiple Web pages (in HTML) are generated by PiLLoW in the order given in the *Content*. The first Web page is named "index.html" and the filenames of other Web pages are based on accident codes (e.g., case101) so that the menu items and their hyperlinks can also be consistently generated. Each accident event is presented in a 3x3 table by `visualisePageContent` in the same manner as `visualisePage`. The schematic pattern of the layout is shown in Figure 4.2. The result of this example is shown in Figure 4.3.

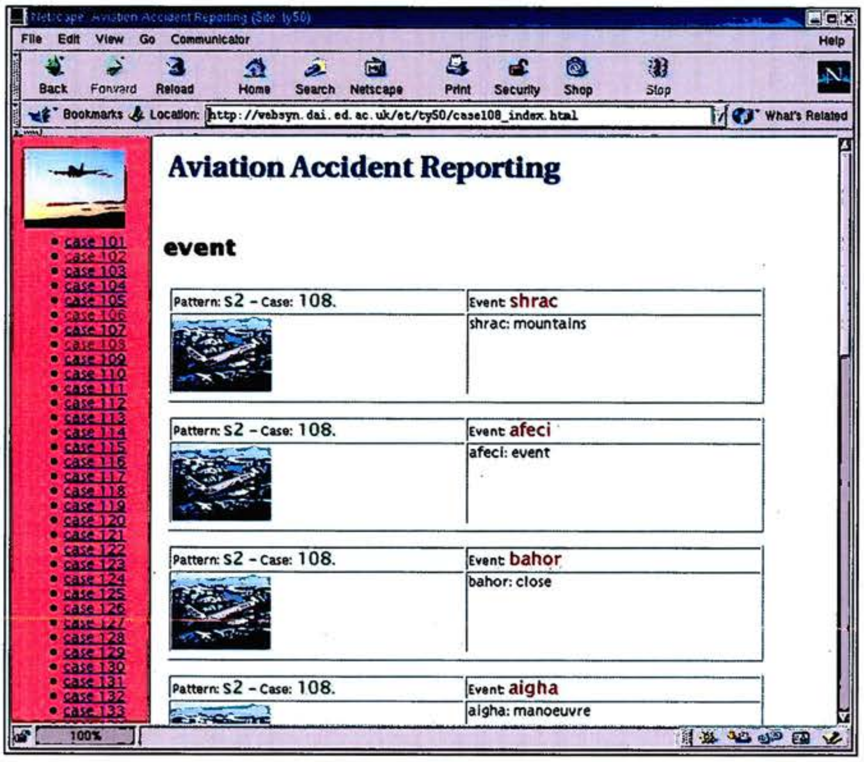


Figure 4.3: A synthetic Website

4.6 Chapter Summary

Website synthesis follows Website design practice. A simple Website interface model (SWiM) is proposed to describe the tasks of Website synthesis and to systematise the specification of Website construction by using grammars. Aviation accident events are used to exemplify how Website synthesis works. During the development of grammars for Website synthesis, we realised that there are numerous alternatives to present the same information and wondered whether the presentation formats would affect the perception of causality of accident events and whether the designers' preference in selecting presentation formats is related to their cognitive abilities, such as visualisation and analogy-making. These hypotheses are explored in later chapters as our examples for using computational synthesis in scientific experimentation.

Chapter 5

Experiment Synthesis

Formulation of experiments is about how to apply treatments to experiment units and to measure the responses of experiment units to different treatments (Cox and Reid, 2000). Treatments are stimuli, each of which is to be given to a particular experiment unit. Experiment units are the subjects (e.g., participants, patients, animals, crops, and raw material) to receive treatments. Responses are the measurable criteria after, and supposed to be effected by, treatments. Statistical experiment design (Cox and Reid, 2000; Grafen and Hails, 2002; Shadish et al., 2002; Montgomery, 2005; Ryan, 2007) has provided statistical methods to optimise the use of resources and to avoid errors and biases in the formulation of experiments. Software toolkits for collecting and processing experimental data are widely available and catalogued[1], particularly paper-based and Web-based interviewing (Birnbaum, 2004; Mizuno, 2004; Skitka and Sargis, 2006). Rather than pursuing statistical experiment design and Web-based interviewing, our approach to experiment synthesis is to explore how the Web is interfaced with or used as an instrument in compliance with experiment protocols and in connection with hypotheses, treatments, experiment units, and responses, This chapter will describe and exemplify how we [partially] synthesised cognitive science experiments, which serve as severe tests for applying computational synthesis to non-computational experiments. The conduct and results of actual experiments will be described in the next two chapters.

[1] `http://www.asc.org.uk/Register/index.htm`

Protocol 3 An experimental research script

- Formulate hypotheses
- ***Design experimental methods***: *variables and statistical design*
- *Obtain available materials and measures*
- *Construct experimental materials and measures*
- Obtain research assistants
- Pilot test procedures and measures
- Refine experiment based on pilot results
- Obtain participants (experiment units)
- ***Data collection***
- Code and organise data
- **Data analysis**
- Determine if hypotheses were supported

5.1 A Grammar for Experiment Synthesis

Most books and papers teaching experimental research cover similar ideas, i.e., hypothesis generation, experiment design, data collection, and data analysis. These ideas may be used to formulate experimental research. An empirical study (Hershey et al., 1996, 2006) showed that researchers describe common steps (script / protocol) in their research. Forty nine psychology professors were recruited from major academic institutions and each was asked to list about twenty actions or steps that characterise his / her experimental research work. Consensual steps in between the hypothesis generation and data analysis were shown in Protocol 3 as a composite research script. This indicates that the interviewed researchers agree very much about important steps in experimental research. The steps in boldface are commonly discussed in various textbooks of experimental methods (Cox and Reid, 2000; Grafen and Hails, 2002; Shadish et al., 2002; Montgomery, 2005; Leong and Austin, 2006; Ryan, 2007). The steps in italic typeface are the ones which could make use of computational synthesis. These possibly computational steps may form a grammar for a simple pattern of experiment synthesis:

$$\frac{e(E) \rightarrow t(T), b(B), u(U), a(A), r(R), d(D)}{\begin{array}{l} carriers(E, T, B, U, A, R, D) \wedge \\ (T \cup B \cup U \cup A \cup R \cup D) \subseteq E \end{array}}$$

where e stands for the protocol specification of experiment with some specific attributes (E), t stands for the protocol specification of treatments with some specific attributes (T), b stands for the protocol specification regarding the measurements of background (or controlled background) conditions with some specific attributes (B), u stands for the protocol specification about experiment units with some specific attributes (U), a stands for the protocol specification about allocation (assignment) of treatments t to experiment units u with some specific attributes (A), r stands for the protocol specification regarding the measurements of responses with some specific attributes (R), and d stands for the protocol specification of data analysis with some specific attributes (D). All attributes should satisfy the carriers which put all protocol specifications together for experimentation.

At the present stage of development, our grammars do not prescribe a continuity for total synthesis of experiments. Many of the steps of transformation described by the grammars still need experimenters to add materials and procedures (e.g., instruments) as given components to fill the gaps. Different experimenters may develop their grammars to suit specific kinds of experiments.

5.2 Computational Synthesis of Experiments

Formulated hypotheses are theoretical constructs of the scientific inquiry of interest. They must be further formalised into variables for experimentation. To use these variables for manual or computational synthesis of experiments, we can develop an initial specification and then refine/elaborate it to build an experiment. An example for such initial specifications is given in Figure 5.1. Some independent variables are operationalised as treatments (including experiment controls). Dependent variables are the responses of the experiment units to be observed and measured. Given the experiment units and treatments, one treatment is applied to each unit and one response is measured on each unit so that the effects of the treatments on the units can be estimated (Cox and Reid, 2000).

Sophisticated experiments can be too complicated to fully specify. However, partial specifications would be feasible even when no total synthesis of experiment has been achieved. In Chapters 6 and 7 we describe two experiments. The experiment in Chapter 6 is specified using the simple morgan of Figure 5.1 to start the synthesis of an experiment, which aims to investigate whether and how the independent variables (i.e., (1) the covariation of aviation accident events, (2) the arrangement of events in causal or temporal orders, and (3) the events presented in sensible or cryptic terminology) would affect the perception of causality in the presented aviation accident events, i.e., the dependent variable. The experiment specification provides information about independent variables, dependent variables, background variables, experiment unit variables, and treatment variables. Independent variables, together with the treatment variable, are considered in formulating individual conditions for treatments. Dependent variables are the responses to be measured before, during, and/or after the treatments. Background variables describe controlled and/or non-manipulative conditions which should not affect the dependent variables although present in the experiment. Background variables are sometimes measured before, during, and/or after the experiment to rule out confounding errors. Experiment unit variables describe the experiment units, i.e., the subjects, being sampled, treated and measured.

Individual parts of experiment synthesis need partial information about the experiment as a whole. As prescribed in the grammar for experiment synthesis, we can distribute the required subset of full information into separate morgans, e.g., treatments (Figure 5.2), background measurement (Figure 5.3), response measurement (Figure 5.4). It would be preferable that each part of experiment synthesis is conducted according to each subunit morgan. For example, independent variables are used to synthesise treatments. Measurements of background conditions are used to synthesise something required for data collection of conditions and background information. Dependent variables are used to synthesise response measurement as a part of data collection. These parts of synthesis for Web experiments can be realised by using Web-based materials, including instruments, as components.

$$
\begin{array}{c}
\textsf{experimentSpec}\\
\left[\begin{array}{l}
\hfill\textsf{independentVariables}\hfill\\
\left[\begin{array}{ll}
\quad\textsf{rhetorics} & \quad\textsf{terminology}\\
\left[\begin{array}{l}
varType : categorical\\
varLevels : causal, temporal\\
varUse : moderating\\
varTreatment : independent
\end{array}\right] &
\left[\begin{array}{l}
varType : categorical\\
varLevels : sensible, cryptic\\
varUse : moderating\\
varTreatment : independent
\end{array}\right]\\
\quad\textsf{covariation} & \\
\left[\begin{array}{l}
varType : categorical\\
varLevels : c1...c5\\
varUse : causal\\
varTreatment : repeatedMeasure
\end{array}\right] &
\end{array}\right]\\
\textsf{dependentVariables}\\
\left[\begin{array}{l}
\quad\textsf{causalRatings}\\
\left[\begin{array}{l}
varType : interval\\
varLevels : 0...100\\
varUse : measurement
\end{array}\right]
\end{array}\right]\\
\hfill\textsf{backgroundVariables}\hfill\\
\left[\begin{array}{lcl}
\quad\textsf{bV1} & \dots & \quad\textsf{bVn}\\
\left[\begin{array}{l}
varType : ordinal\\
varLevels : 1...7\\
varUse : measurement
\end{array}\right] & &
\left[\begin{array}{l}
varType : ordinal\\
varLevels : 1...7\\
varUse : measurement
\end{array}\right]
\end{array}\right]\\
\textsf{experimentUnits}\\
\left[\begin{array}{l}
unitType : humanSubjects\\
samplingMethod : convenience\\
sampleSize : 40
\end{array}\right]\\
\textsf{treatmentAllocation}\\
\left[\begin{array}{l}
assignment : randomised
\end{array}\right]
\end{array}\right]
\end{array}
$$

Figure 5.1: An example morgan as a starting material for experiment synthesis

$$
\begin{array}{c}
\textsf{treatments} \\
\begin{bmatrix}
\begin{array}{c}\textsf{independentVariables}\end{array} \\
\begin{bmatrix}
\begin{array}{cc}
\textsf{rhetorics} & \textsf{terminology} \\
\begin{bmatrix}
\mathit{varType} : \mathit{categorical} \\
\mathit{varLevels} : \mathit{causal}, \mathit{temporal} \\
\mathit{varUse} : \mathit{moderating} \\
\mathit{varTreatment} : \mathit{independent}
\end{bmatrix}
&
\begin{bmatrix}
\mathit{varType} : \mathit{categorical} \\
\mathit{varLevels} : \mathit{sensible}, \mathit{cryptic} \\
\mathit{varUse} : \mathit{moderating} \\
\mathit{varTreatment} : \mathit{independent}
\end{bmatrix} \\
\textsf{covariation} & \\
\begin{bmatrix}
\mathit{varType} : \mathit{categorical} \\
\mathit{varLevels} : c1...c5 \\
\mathit{varUse} : \mathit{causal} \\
\mathit{varTreatment} : \mathit{repeatedMeasure}
\end{bmatrix} &
\end{array}
\end{bmatrix}
\end{bmatrix}
\end{array}
$$

Figure 5.2: An example morgan for synthesising treatments

$$
\begin{array}{c}
\textsf{background} \\
\begin{bmatrix}
\begin{array}{c}\textsf{backgroundVariables}\end{array} \\
\begin{bmatrix}
\begin{array}{ccc}
\textsf{bV1} & \ldots & \textsf{bVn} \\
\begin{bmatrix}
\mathit{varType} : \mathit{ordinal} \\
\mathit{varLevels} : 1...7 \\
\mathit{varUse} : \mathit{measurement}
\end{bmatrix}
& &
\begin{bmatrix}
\mathit{varType} : \mathit{ordinal} \\
\mathit{varLevels} : 1...7 \\
\mathit{varUse} : \mathit{measurement}
\end{bmatrix}
\end{array}
\end{bmatrix}
\end{bmatrix}
\end{array}
$$

Figure 5.3: An example morgan for background measurements

$$\begin{matrix}\textsf{response}\\ \left[\begin{matrix}\textsf{dependentVariables}\\ \left[\begin{matrix}\textsf{causalRatings}\\ \left[\begin{array}{l} varType : interval \\ varLevels : 0...100 \\ varUse : measurement \end{array}\right]\end{matrix}\right]\end{matrix}\right]\end{matrix}$$

Figure 5.4: An example morgan for response measurements

5.3 Synthesis for Treatments

Treatments are the stimuli or conditions given or applied to experiment units (e.g., participants) so that the responses of the experiment units to different treatments can be measured in the experiment. The materials for treatments in Web experiments are basically Websites or Web documents suitable for the domain for testing in experiments. As aviation accident reporting requires high accuracy and efficiency in presenting and perceiving causal relationship among all relevant accident events, we used the domain of aviation accident reporting in our experiments for testing the perception of causality (Chapter 6) and the preference in selecting presentation formats (Chapter 7). For synthesising Web materials for the example experiments, we arranged aviation accident events as the given information in specific ways to serve as treatments. All accidents belonging to a treatment for an experiment unit (participant) were presented on a single Website. Events of an aviation accident were presented on one or more Web pages. The events were presented in English language in natural (although occasionally technical) language. The participants can browse the assigned Website and access each of given aviation accidents by using the Website's main menu. They can also follow individual events according to the presentation order or by using the available hyperlinks on each Web page. The synthesis of the Websites and Web pages are as described in Chapter 4. An example Web page generated for this treatment is shown in Figure 4.3. Here we can focus on the synthesis of different treatments, which are presented as the central content area of the synthesised Web pages.

$$\frac{treatments(VarTypeList) \rightarrow webinfo(ContentList)}{\begin{array}{l} factorialDesign(VarTypeList, GroupTreatmentList) \wedge \\ givenInfo(Info) \wedge \\ groupTreatment(GroupTreatmentList, Info, ContentList) \end{array}}$$

where *treatments(VarTypeList)* represents the treatment specifications such as shown in Figure 5.2, *factorialDesign(VarTypeList, GroupTreatmentList)* represents the experiment design layout, *givenInfo(Info)* represents the Web content information (i.e., aviation accident events in our example) given for synthesising the Websites as treatments, *groupTreatment(GroupTreatmentList, Info, ContentList)* represents a high level goal to arrange the given Web content information, according to each treatment group specification, into Website content for all treatment groups. Specific arrangements of the given information are made by respective instruments.

Each event was presented in a table (box), which was divided into cells to display the information of event names, event description, pictorial icons indicating the flight positions (e.g., climb, cruise, and land), etc. An example event (named "e") is specified in Figure 5.5, in which the attributes *eName* and *eCrypticName* are respectively meaningful and cryptic terms for the event (allowing experiments with and without meaningful terms for events). The attributes *eAltitude* and *eDIstance* indicate the altitude of the plane from sea level and distance of the plane from destination airport. The attribute *eTime* indicates the time of the event.

5.3.1 Rhetorics in Presenting Information

The same source information can be presented in different ways and certain ways are more effective or efficient to achieve our communication goals. This is where rhetoric is important. The Web as an instrument can help model the information and knowledge to comply with rhetorics. For example, we can present aviation accident events. We can present the events in temporal sequence rather than the given causal tree structure. We can present the events according to the positions of aircraft at different time points. We can present the events in graphical accidentEvents

e

eState : cruise
ePicture : http://websyn.dai.ed.ac.uk/images/lackpower.jpg
eCrypticName : kiodwa
eName : PassengerReport
eDesc : Passengers told flight attendants about sparks from engine A
eAltitude : 1023
eDistance : 13.5
eTime : '19:03:15'

...

Figure 5.5: An example morgan for specifying an aviation accident event

```
% cause(+EventList, +Consequence)
cause([p,i], h).
cause([h], g).
cause([y,z,e,g], d).
cause([w], e).
cause([d], b).
cause([b], a).
```

Figure 5.6: An example causal structure of aviation accident events

trees or text tables. These rhetorics of presentation were tested in our example experiments to exemplify experiment synthesis.

5.3.1.1 Tabular Presentations

A temporal sequence of the events can be generated by sorting according to the given attribute *eTime*. Possible causal structures of the events of an aviation accident were given and can be represented in a hierarchical structure as shown in Figure 5.6. In our example, the events in temporal order were linearly presented on a Web page. The causal structure of the events required multiple Web pages to be presented with each Web page presenting the events that happened at the same time slot. Each presented event had hyperlinks to link to its candidate causes and likely consequences, which could be on the same or a different Web page, thus allowing the causal structure from Figure 5.6 to be navigated.

5.3.1.2 Graphical Presentations

As the information about the time, altitude, and distance (from runway) is available, it is possible to visualise the position of aircraft in a graph, e.g., X-axis as time, Y-axis as altitude, and Z-axis as the distance from runway. Before we can generate this graph, we put these pieces of information together into a table from relevant events by a simple facility based on a temporal logic interpreter. To get information from events as specified in Figure 5.5, we use the following rule:

$$\frac{events(EventList) \rightarrow table(AircraftPositions)}{collection([eTime, eAltitude, eDistance], EventList, AircraftPositions)}$$

Suppose we have only three different time points at which altitude and distance from runway were known then the pairs of values for the instantiated table providing position information in terms of time, mean sea level, and nautical miles might be:

```
table([('10:15:05',1023,13.5),('10:42:20',876,9.25),('10:49:42',833,6.25)])
```

These data can be used to generate a graph to visualise the positions of aircraft in different time points or events. An example graph with more information is shown in Figure 5.7.

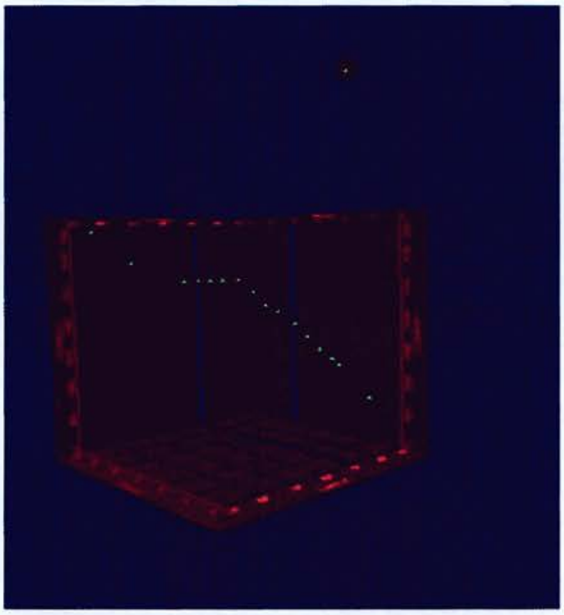


Figure 5.7: A 3D graph displaying the altitude and distance positions of aircraft at different time points

In addition to temporal presentation in 3D graphics, the causal tree structure of accident events can be presented in graphical form (Figure 6.1). The causal trees can be generated from GraphViz[2] and embedded in Web pages. In both table and tree forms of presentation, there are multiple attributes available for presenting different attributes of accident events. The attributes of tree presentation include nodes and edges between nodes. The attributes of each node or edge may include the code, name, and text to be [only] shown when a mouse pointer moves over the item. The attributes of an instantiated tree are shown in Figure 5.8, as a result of attribute mapping between a morgan of an accident event and a morgan of a causal tree. The result of preferred mapping can be fed into the Website synthesiser to generate the desired trees. The same principle is applicable to generating tables. In one of our example experiments, participants were asked to test various possible mappings and to generate a Website on the fly for each mapping.

[2] `http://www.graphviz.org`

$$
\begin{bmatrix}
\text{tree-graph} \\
\begin{bmatrix}
\text{tree} \\
\begin{bmatrix}
\text{node1} \\
\begin{bmatrix}
\mathit{nodeName}: \text{PassengerObservation} \\
\mathit{nodeMouseOver}: \text{Passengers saw sparks from engine A}
\end{bmatrix} \\
\ldots \\
\text{edge1} \\
\begin{bmatrix}
\mathit{edgeName}: \text{PassengerReport} \\
\mathit{edgeMouseOver}: \text{Passengers told flight attendants about sparks from engine A} \\
\mathit{nodeFrom}: \text{node1} \\
\mathit{nodeTo}: \text{node2}
\end{bmatrix}
\end{bmatrix}
\end{bmatrix}
\end{bmatrix}
$$

Figure 5.8: An example morgan for specifying an aviation accident event

5.3.2 Technical Terminology

To control for differences of prior knowledge among the participants about aviation accidents, in one of our experiments, we used meaningful description for accident reports or cryptic (fragmentary and not informative) description in separate treatment groups.

5.3.3 Cause-effect Covariations

To generate fictitious accidents, we follow the causal tree structures of real aviation accidents. The same structure may represent accidents and non-accidents (given that events happened to avoid accidents). By using the causal trees and a given frequency of a cause causing accidents, information about multiple fictitious accidents can be generated and presented on Web pages.

$$\begin{array}{c}\textsf{experimentUnits}\\ \left[\begin{array}{l} \mathit{unitType} : \mathit{humanSubjects} \\ \mathit{samplingMethod} : \mathit{convenience} \\ \mathit{sampleSize} : 40 \end{array}\right]\end{array}$$

Figure 5.9: An example morgan for experiment units

5.4 Experiment Units

The basic information for specifying experiment units are as shown in Figure 5.9. According to the information of this example morgan, experimenters need to find 40 human subjects as recruited by means of convenience (non-random) sampling. Experiment units are seldom synthesisable. In cognitive science, experiment units are usually human subjects, who are not the objects of experiment synthesis. We recruited student volunteers in the university for cash rewards in one experiment. We also asked students in a course module to participate in another experiment as one of their laboratory sessions, during which the participants as experiment units were randomly assigned treatments.

5.5 Data Collection

As questionnaire generators are readily available as our instruments, we did not synthesise questionnaires using our Website synthesiser. Questions were handcrafted and fed into a questionnaire generator toolkit (modsurvey[3]) to obtain Web questionnaires for data collection. There are thousands of standardised questionnaires and response tests, e.g., Test in Print[4] and ETS Test Collection Catalogue[5], available as instruments in psychology and cognitive science. Of course, most cognitive scientists still cannot find suitable tests for their creative

[3] `http://www.modsurvey.org`
[4] `http://www.unl.edu/buros`
[5] `http://ets.org`

experiments.

For measuring the background variables such as the knowledge of participants about computer and aviation accidents, we need a questionnaire to be filled in by participants before the experiment. We found and modified a sample questionnaire for computer background knowledge from a questionnaire generator toolkit (modsurvey). We also add a few questions about the participants' knowledge about aviation accidents. The measurement of background variables like these aims to ensure there is no significant background differences among different treatment groups. The pre-experiment questionnaire for measuring background variables is shown in Appendix B.

For measuring the response variables concerning simple causal perception in our example experiment, we follow the question formats used in the causal perception experiments published by other experimenters. For measuring counterfactual causal perception, we just change the question wordings to be counterfactual (see the response measurement questionnaire in Appendix C).

5.6 Reusable Parts of Experiments

Reusability of the experiment components should be high in similar laboratories conducting related research. The most obvious reusable parts of experiments are published test toolkits (instruments). We did two experiments of different kinds (causal vs. correlational) and with different objectives. The first experiment is to present accident events on Websites to test the causal perception of participants. The second experiment is to allow participants to try different possible mappings between information and presentations (tables or trees). Despite these differences, they share the same Website synthesiser and presentation mechanism of the aviation accident events.

5.7 Synthetic Web-based Experiments

For Web-based experimentation, we can use synthetic Web materials as instruments to model knowledge, provide working knowledge, and/or conduct measurements. As the synthesis process is repeatable and the modifications can be done at a higher level, the advantages of using synthesised Websites in Web-based experiments are:

- saving time and effort of the experiment (often the key to enabling it) ;
- maintaining Website consistency throughout the experiment;
- reproducing the experiment;
- facilitating the modifications of the experiment after pilot tests; and
- modifying the Websites for other experiments.

The example experiments as described in the next two chapters demonstrate some of these advantages.

5.8 Chapter Summary

This chapter demonstrates a use of experiment synthesis in constructing experiments. Experiment synthesis starts with specifications of important parameters and proceeds by using parameterisable components as the instruments for experimentation. Under the paradigm of the Lab-on-the-Web as we envisaged, such instruments are interfaced with or actually are the Web-based materials. Physical instruments interfaced with the Web are controlled by appropriate parameters of experiments. Web-based materials can be organised and visualised by using Website synthesis techniques in accordance with the specified parameters. With Website synthesis techniques, experiment synthesis should make Web-based experiments easier to construct, conduct, reproduce, modify, and extend. To demonstrate the use of experiment synthesis in non-computational experiments, we will use it for non-trivial cognitive science experiments in the next two chapters. The first one is a causal experiment and the second one is a correlational experiment.

Chapter 6

Synthesised Experiment 1: Causal Perception

Our aim is to demonstrate computational synthesis of Web-based experiments in undertaking experimentation on (1) causal perception which is seen to be a cognitive basis of science (Hilton, 2002) and (2) representation mapping (design) where cognitive science should contribute (Stary and Peschl, 1998). This chapter describes the experiment on causal perception and the next chapter will explore the experiment on representation mapping, particularly the correlation between some cognitive factors (visualisation and analogy-making) and the mapping (design) preference for two different modalities of presentation formats (tables and graphics).

The experiment on causal perception aims to test different causal perception theories in the application of aviation accident reporting. In addition to the normal causal perception, the participants were also prompted for their counterfactual causal ratings. The rhetorics and modality may influence the effectiveness (e.g., accuracy and completeness), efficiency (e.g., resources for achieving goals), and satisfaction (e.g, comfort and acceptability) of the presentation. As we are not sure whether rhetorics (e.g., the patterns of presentation sequences) and modality (e.g., the perceptual forms of the presented material for stimulus) of presentation would affect people's causal perception (or their confidence) of aviation accident reports, we also introduced these two factors.

6.1 Causal Perception Models

Causal perception is an old philosophical issue (as briefly described in Chapter 2) and more recently became an area of active research in cognitive science (Hilton, 2002). Some hypotheses have been proposed to describe the relationship between the perception of causal relations and the covariation information, which can be formulated by using the terms in the following contingency table.

	Effect occurs	
Candidate cause	Yes (e^+)	No (e^-)
Present (c^+)	c^+e^+	c^+e^-
Absent (c^-)	c^-e^+	c^-e^-

The hypotheses of causal perception we tested are, first, the Contingency model (see for example (Cheng and Novick, 1990)) which predicts a measure, ΔP, of the extent to which a candidate cause, c, and an effect, e, are perceived to covary according to the equation:

$$\begin{aligned}\Delta P &= P(e \mid c) - P(e \mid \neg c)\\ &= (c^+e^+/(c^+e^+ + c^+e^-)) - (c^-e^+/(c^-e^+ + c^-e^-))\end{aligned}$$

where $P(e \mid c)$ is the probability of e given that c occurs and $P(e \mid \neg c)$ is the probability of e given that c does not occur. ΔP is often called contingency or contrast.

The second hypotheses of causal perception is the Probabilistic Contrast (PC) model, so called the Power PC model (compared to the contingency model in (Glymour, 2001; Lien and Cheng, 2000)), as defined below:

$$PC = \Delta P/[1 - P(e \mid \neg c)] = \Delta P/[1 - c^-e^+/(c^-e^+ + c^-e^-)]$$

where PC is the generative power of c with respect to e.

There is no consensus over which model is more approximate to describe the regularity of causal perception in general. For our own application in aviation accident reporting, we aim to test which causal perception model would be more applicable.

6.2 Factors Affecting Causal Perception

Our two causal perception models take into account only the main contributing factor, i.e., covariation information of candidate causes and effects. Other factors such as how the causal information is presented may affect the causal perception are not considered. Recent studies such as those on the interaction between multiple causal cues (Lovibond et al., 2003), the correlation of beliefs and causal perception (Fugelsang and Thompson, 2000, 2001, 2003; Fugelsang et al., 2006), the cause-effect delays in time (Buehner and May, 2003), the agreement between counterfactual and factual thinking (Mandel, 2003), familiarity and imageability of the candidate causes and effects (Fugelsang et al., 2006), and the difference in the question wordings for probing the causal ratings (White, 2003) show that many complex factors can legitimately be introduced. Most of these factors were uncontrolled in the past experiments, so experimentally it would ideally be necessary to determine whether the causal perception would be affected by some of the factors other than covariation information of candidate causes and effects.

6.3 Objectives and Hypotheses

For aviation accident reporting, the ways to present accident information on Websites might influence perception of the causes of accidents. We would like to find:

- which causal perception model as described in Section 6.1 is the closest approximation to the observed perception under our specific scenarios – aviation accident reporting on Websites;
- any correlation between the normal and counterfactual causal perception ratings; and
- whether the observed perception ratings are influenced by factors other than covariation information of candidate causes and effects, e.g., temporal / causal rhetorics and sensible / obscure terms.

We shall consider two different forms of rhetoric: a strongly causal rhetoric in which the causal links between events (known from the accident patterns used to generate the sites) are emphasised as hyperlinks between events; and a temporal rhetoric in which the sequence of events for each accident is shown and causal links are mentioned but not emphasised. To determine the effect of subjects using their own background knowledge of aviation accidents, we generate sites for some of the experiments using event descriptions meaningful to aviation (such as "speedbrake extended") and for other experiments we generate the same causal description but with cryptic names unrecognisable in the aviation domain.

These models give different predictions of the causal strength associated with a cause and an event. For instance, if the probability of an event given that a cause occurs ($P(e \mid c)$) is 0.9 and the probability of the event given that the cause does not occur ($P(e \mid \neg c)$) is 0.8 then contingency model predicts the strength of causation to be 0.1 while power PC predicts 0.5. By setting up Websites describing sets of accidents with known $P(e \mid c)$ and $P(e \mid \neg c)$, which is very time consuming to do by hand, we can assess the predictive power of these two models by comparing their predictions to those observed from human subjects who have browsed those sites.

The null hypotheses in the experiments described below are:

1. Causal perception of aviation accidents is random and does not follow any causal model.
2. Causal perception of accidents would not be affected by different styles of the information being presented.
3. Normal causal ratings are the same as counterfactual causal ratings.
4. Confidence scores in giving both normal and counterfactual causal ratings are the same.

6.4 Methods

6.4.1 Participants

The participants were 47 undergraduate students of the University of Edinburgh, taking the Artificial Intelligence module as one of the three constituents of their first year of study. The experiment was run in Semester 2 during the experimental methodology module of the course. The course attracted students from a broad variety of science and engineering disciplines (also including psychology and linguistics degrees). Their computer training in the course modules earlier in the year should have equipped them with basic computer skills and are familiar with Web browsing. The participants were allocated to four different groups in a random sequence of four group numbers.

6.4.2 Generating Websites

We generated different Websites (one for each participant) containing 100 accident cases from the same accident patterns. The Websites in this experiment were synthesised via the automated process described in Chapters 4 and 5. The synthesiser can be parameterised by the rhetorical and terminological style and could also be set to generate a sample of accident cases with the combinations of covariations shown in the table of the previous section. These samples were generated from standard patterns of aviation accident culled from the literature.

Five patterns of aviation accident information having the same causal structure were randomly assigned to the five combinations of covariation of candidate causes and accidents. This avoided the influence of specific accident information content on the causal perception test. The diagram of Figure 6.1 shows an example pattern of aviation accident information:

This aviation accident information was used to synthesise the experimental Websites. As an additional measure, the hyperlinks of each synthesised Website were automatically checked for errors such as dead links, raising our confidence (although of course not guaranteeing) that our synthesiser had worked reliably. Every Website was thus guaranteed to be unique in terms of the settings of rhetoric, terminology, and the order of presenting cases.

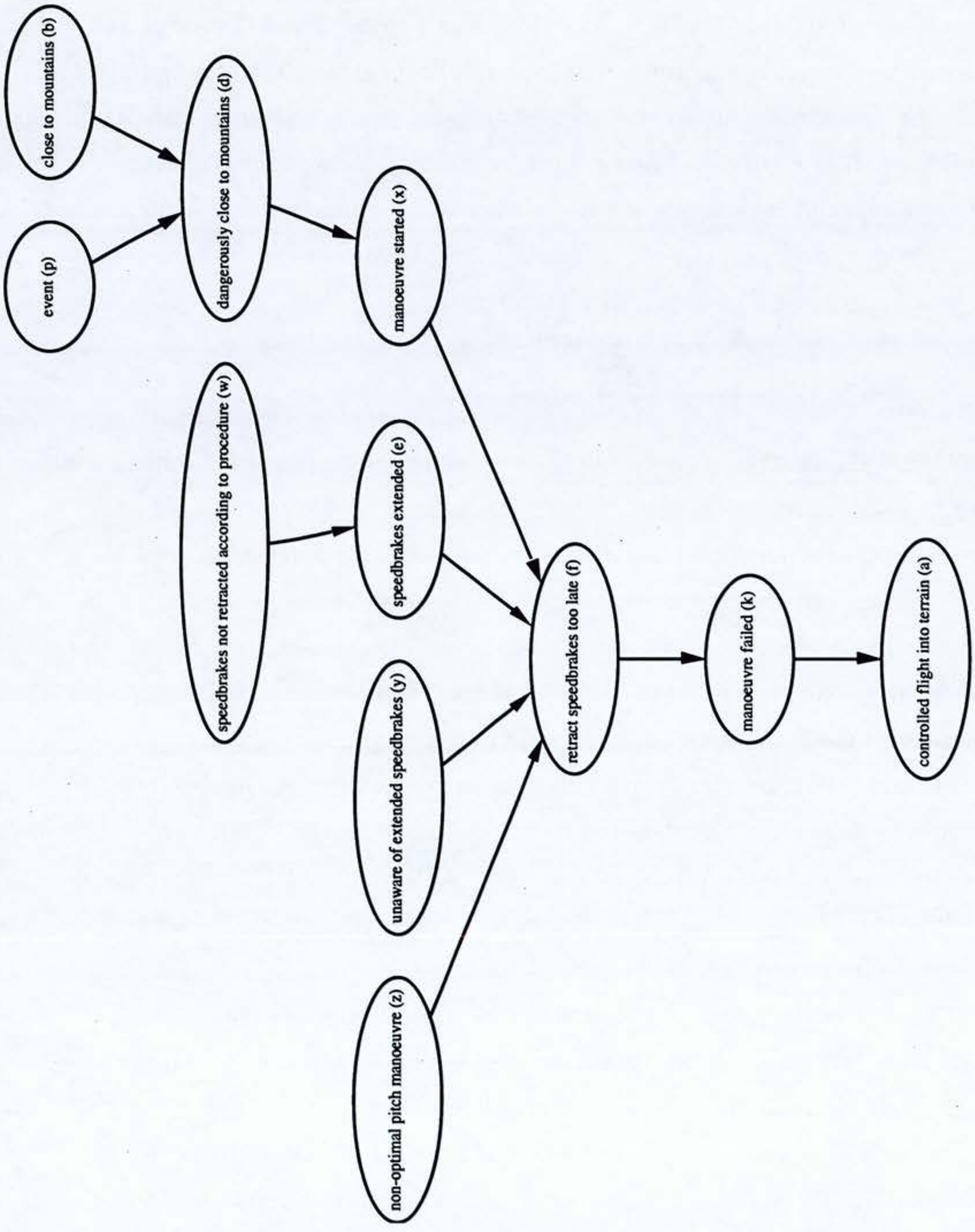


Figure 6.1: An example of aviation accident pattern

6.4.3 Experiment Design

The dependent variables were normal causal ratings and counterfactual causal ratings. The values of normal causal rating and counterfactual causal rating were expressed on a scale between 0 and 100. The wording of the question to probe normal causal rating was as follows, where *AccidentCategory* describes a type of accident and *EventName* describes a type of event:

> "Out of each 100 flights without an accident [*AccidentCategory*], how many might have had an accident [*AccidentCategory*] if [*EventName*] had occurred? (0-100)"

The wording of the question to probe the counterfactual causal rating was as follows:

> "Out of each 100 flights with an accident [*AccidentCategory*], how many might not have had an accident [*AccidentCategory*] if [*EventName*] did not occur? (0-100)"

The participants were also asked to rate their confidence in giving their normal causal rating and counterfactual causal rating. These confidence ratings were acquired using a 7-point scale.

The independent variables are positive covariation frequency $P(e \mid c)$ and negative covariation frequency $P(e \mid \neg c)$, where e is an accident (effect) and c is each candidate cause. The corresponding versions of the ΔP and PC models are described in Section 6.1.

Other independent variables are rhetoric and terminology. The only two possible choices of rhetoric are *causal* and *temporal.* Using causal rhetoric ensures that the events in each aviation incident described by a site are arranged using causal relations, i.e., an event is caused by another event and may lead to zero or more other events (Figure 6.2). Using temporal rhetoric ensures that the events in each aviation incident described by a site are arranged simply according to their temporal sequence, i.e., two adjacent events on display may not have causal relationship (Figure 6.3). The two possible choices of description are *sensible* and *cryptic.* Choosing sensible description ensures that each event is described using an English phrase which is normally used to describe such an event when reporting an incident (Figure 6.2). Choosing cryptic description ensures that the

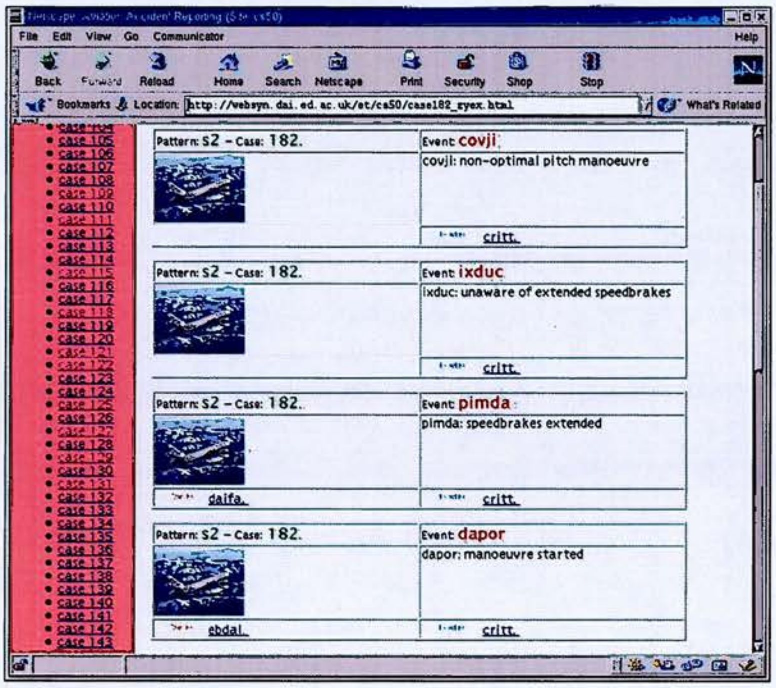


Figure 6.2: A Website with causal rhetoric and normal technical description

events are described using arbitrary terms which are meaningless as far as aviation incidents are concerned (Figure 6.3). The cryptic description was used as a check that our human subjects were not using pre-conceptions of description to influence their causal judgement.

6.4.4 Rhetorics of presentation

Each synthesised Website as the apparatus of this experiment presented the aviation accident information in one of the following styles:

1. Multiple pages per case with hyperlinks indicating causal relations of the events (causal rhetoric) and description using common terminology (sensible terminology).

2. Multiple pages per case with hyperlinks indicating causal relations of the events (causal rhetoric) and description using cryptic terminology (cryptic terminology).

Figure 6.3: A Website with temporal rhetoric and cryptic description

3. Single page per case with the events appearing in temporal sequence (temporal rhetoric) and description using common terminology (sensible terminology).

4. Single page per case with the events appearing in temporal sequence (temporal rhetoric) and description using cryptic terminology (cryptic terminology).

Each synthesised Website presented five patterns of aviation accidents with five different combinations of covariations between candidate causes (ca) and accidents (ac). For each of these, we can calculate the values of $P(e \mid c)$ and $P(e \mid \neg c)$, thus allowing us also to calculate the predictions of the ΔP and PC models for each combination. These calculations are shown in the table below.

Combination	$P(e \mid c)$	$P(e \mid \neg c)$	ΔP	PC
A	1.0	0.5	0.5	1.0
B	0.9	0.8	0.1	0.5
C	0.8	0.5	0.3	0.6
D	0.7	0.5	0.2	0.4
E	0.6	0.2	0.4	0.5

6.4.5 Tasks and Procedures

Each participant began by filling out a pre-experiment questionnaire (see Appendix B) on the Web collecting their personal information such as year of birth, programme of study, levels of computer and Web skills, current usage of computers and the Web, and familiarity of aviation operations. Subsequently, each participant logged in the Website which was randomly assigned to him/her to browse. Each participant was also given instructions concerning how to browse the synthesised Websites, particularly how to interpret the provided navigation aids and estimate the frequencies of the given potential causes and effects. Each Website presented 100 cases of aviation accidents and incidents. The browsing task took about 45 minutes. The participants were asked to pay attention to the occurrence and to record the frequency of candidate causes and effects. The participants were given the correct data about the co-occurrence of the candidate causes and effects on the Websites they had already browsed. Then each participant proceeded to fill in a post-experiment questionnaire (see Section 6.4.3 for question templates) on the Web in order to give normal causal ratings and counterfactual causal ratings.

6.4.6 Data Analysis

Independent variables are (1) the combinations of covariation of candidate causes and accidents (within subjects), (2) rhetoric (causal or temporal), and (3) terminology (sensible or cryptic). Dependent variables are (1) normal causal ratings, (2) scores of confidence in giving the normal causal ratings, (3) counterfactual causal ratings, and (4) scores of confidence in giving the counterfactual causal ratings. Background information collected in the pre-experiment questionnaires was also analysed against the independent variables to ensure the homogeneity of participants among rhetoric and terminology groups of treatment. The data were analysed by the Student's t-test, the analysis of variance (ANOVA), Krustal-Wallis test, and linear regression, using R[1] statistical software (R Development Core Team, 2007). P values less than 0.05 were considered statistically significant.

6.5 Results

We summarise the results of the experiment in this section and will discuss them in Section 6.6.

6.5.1 No significance in the background among groups

Our pre-experiment questionnaire was intended to detect imbalance in the social or technical background of the participants. There was no significant difference detectable by ANOVA and Krustal-Wallis tests in all answers to the pre-experiment questionnaire among the participants in different treatment groups. Hence, no significant bias due to the background of the participants was found among the different groups.

6.5.2 No significance in rhetorics and terminology factors

Using a post-experiment questionnaire (see Section 6.4.3 for question templates), we asked the participants of different treatment groups for estimates of normal causal ratings and counterfactual causal ratings. No significant differences in normal and counterfactual causal ratings were found by ANOVA among different treatment groups. In addition, there was also no significant difference detected by ANOVA among different groups in the confidence scores when the participants gave their normal and counterfactual causal ratings. It appears that the tested rhetoric and terminology factors are not likely to be significant influential factors affecting normal and counterfactual causal perception in this experiment.

[1] `http://www.r-project.org`

6.5.3 Significant difference between normal and counterfactual ratings

There was a highly significant difference (t=9.69, $P < 0.001$) and no correlation ($r^2 = 0.04$, $P < 0.001$) between normal and counterfactual causal ratings given to the same scenarios. There was a highly significant difference in the confidence scores given by the participants to their own corresponding normal and counterfactual causal ratings ($t = 5.48$, $P < 0.001$). However, the confidence scores given to normal causal ratings are correlated with those given to counterfactual causal ratings (r^2=0.62, $P < 0.001$). Confidence in normal causal ratings was higher than that in counterfactual ratings, even though both kinds of confidence were highly correlated.

6.5.4 Normal causal ratings were closer to PC

The median and mean normal causal ratings were well predicted by the Power PC model of causal perception as shown in Table 6.1, in which the first two columns show the theoretical causal ratings as ΔP and PC.

Table 6.1: Causal ratings

Models		Normal			Counterfactual		
ΔP	PC	Median	Mean	SD	Median	Mean	SD
0.5	1.0	0.9	0.72	0.29	0.40	0.40	0.20
0.1	0.5	0.5	0.56	0.28	0.25	0.30	0.20
0.3	0.6	0.6	0.57	0.20	0.38	0.40	0.18
0.2	0.4	0.4	0.48	0.20	0.33	0.39	0.18
0.4	0.5	0.5	0.48	0.16	0.40	0.42	0.26

There was a significant difference ($t = 3.80$, $P < 0.001$) between the root-mean-square distances (RMSDs) of normal causal ratings to the theoretical ΔP and PC. The RMSDs with a mean of 0.11 and a standard deviation (SD) of 0.04 between the normal causal ratings and theoretical PC was less than the RMSDs with a mean of 0.15 and a SD of 0.06 between the normal causal ratings and theoretical ΔP. This indicates that the normal causal ratings are closer to

PC than ΔP. By contrast, the counterfactual causal ratings had a statistically significant difference ($t = 6.35$, $P < 0.001$) and were closer to ΔP (mean = 0.10, SD = 0.04) than PC (mean = 0.16, SD = 0.04) in terms of RMSDs.

6.6 Discussion

The results of this experiment support the view that the normal causal ratings are closer to PC than ΔP. The present study is (1) the first test result reported by independent research, which did not aim to test its own model against others' models of causal perception; (2) the first causal perception test conducted for the application domain of aviation accident reporting; (3) the first causal perception test conducted with moderating factors of rhetoric (causal and temporal rhetoric) and terminology (sensible and cryptic terminology); and (4) the first study using synthetic Websites as the experimental apparatus.

This experiment was designed to test causal perception models under different conditions. Its results showed that the normal causal ratings given by the participants in this experiment were more accurately predicted by the Power PC model (PC) than the contingency model (ΔP) of causal perception. As rhetoric (causal and temporal) and terminology (sensible and cryptic) factors did not significantly affect the causal ratings, it appears that covariation information of the candidate causes and effects is a much more important factor affecting the causal ratings.

The counterfactual causal ratings were significantly different from the normal causal ratings. This indicates that counterfactual causal perception might be different from normal causal perception as prompted by different question wordings. While normal (factual) and counterfactual causal perception agree with each other (Mandel, 2003), the counterfactual causal ratings were closer to ΔP in this experiment. The confidence scores in giving both normal and counterfactual causal ratings are well-correlated. This indicates that the normal and counterfactual causal perception are roughly the same in suggesting the presence of possible causal links but different in the causal strength estimation. However, we could not suggest a definite relationship (1) between normal and counterfactual causal perception, and (2) counterfactual causal perception and the contingency model.

Further experiments would be required to delineate the relationship between normal and counterfactual causal perception. For instance, it would be interesting to investigate whether the difference is subject to expert knowledge and experience in the application domain.

After we did our experiment, we found one more applicable hypothesis, namely the evidential evaluation (EE) model (White, 2002), under which causal perception is a function of the proportion of relevant instances of contingency information that are evaluated as confirmatory for the candidate cause. The EE model proposed a pCI rule as follows:

$$pCI = (c^+e^+ + c^-e^- - c^+e^- - c^-e^+)/(c^+e^+ + c^+e^- + c^-e^+ + c^-e^-)$$

Coincidentally, the pCI values under our experiment conditions are exactly the same as ΔP values. Further experiments would be required to include pCI for comparison under various cause-effect covariation conditions.

With the small sample size of this experiment, we could not rule out any effect of the causal/temporal rhetoric and sensible/cryptic terminology on the causal perception even though no significance was found. We believe that the rhetoric and terminology should provide useful information to influence causal perception or reasoning. Further investigation with a large sample would be necessary to determine the roles (if any) and strengths of the rhetorics and terminologies in causal perception.

For efficiency of browsing and finding the candidate causes and effects, the synthetic Websites in this experiment did not include full accident information. Once some factors affecting the causal perception have been determined, further experiments with more realistic aviation accident reporting Websites may be performed.

In addition to scientific significance, this experiment demonstrates a technological significance in using computational synthesis for scientific experimentation. The materials in this experiment were synthesised computationally according to the experiment specification. Computational synthesis enabled the experimenters to synthesise highly controllable and specific knowledge-based content configuration (see Section 6.4.4) of Websites for each participant to meet the requirements of scientific experimentation. This experiment required a Website describing 100 accident reports (with multiple pages per report depending on the style of view) for each of the 47 participants, and each Website had to be consistent in its structure with an underlying model of causality and rhetorics. This task would not be practical without using computational synthesis. We could not cost-effectively make so many individual Websites by hand and it would be hard to guarantee compliance with the underlying causal model. It is not practical to make this experiment work manually at this scale. It would be impossible manually for this experiment to scale up or be reproduced in many possible ways. If we did not use computational synthesis, the most applicable tools would be Web-based experiment toolkits and Web content management systems. However, Web-based experiment toolkits just use a single manually created Website to present various stimuli. A Web content management system only provides a single pattern for Website architecture. That means we have to develop a specific Website content management system to meet the experiment requirement. Developing the required system is a huge software project and would not be easily affordable. Thus, computational synthesis is a practical solution for experiment synthesis.

6.7 Chapter Summary

The experiment reported in this chapter indicates a closer relationship between normal causal ratings and the Power PC model. It also suggests interesting differences between normal and counterfactual causal ratings, which might be closer to ΔP. Further cognitive science research should be conducted by using similar synthetic Websites to formulate more appropriate models for normal and counterfactual causal perception. This experiment would have been impractical without using computational synthesis.

Chapter 7

Synthesised Experiment 2: Preferences and Cognitive Factors

7.1 Introduction

The manner of external representation (or presentation) could affect our way of working with the internal representation (mentally) and our understanding of the information (Zhang, 1997b), e.g., in cockpit information displays for aviation (Zhang, 1997a), but few results on graphical external representation can be generalised (Scaife and Rogers, 1996).

One problem affecting all websites is that there is no reliable, general and abstract method for predicting the effect of presentation rhetorics and modality on understanding of the information. To improve knowledge communication, we should investigate how sensitive people might be to differences in the way we construct our websites. It would be useful to conduct experiments quickly to compare different models of interpretation of information of a specific domain in particular cases. There may be certain styles of presentation or navigation that are generally demanded by users and can either hinder or support users' ability to interpret the information.

Tabular and graphical representations are common in constructing visual arguments (Oestermeier and Hesse, 2000) and presenting relational data (especially quantitative data) (Zhang, 1996). Visualisation of aviation accident events generally use causal trees to represent the causal relations but there are few empirical studies on both preference and perception of causality visualisation. Specifically, we investigate users' preferences for information visualisation styles and their perception of causality as required by aviation accident reporting. As the web is one of the main channels for publishing information of aviation accidents, it is desirable to know about how people would prefer the causal relations in accident events to be presented in a website and how they perceive this causality. The user preference data are useful in the design and re-design of Websites. To elicit preferences from people, it is useful to have multiple designs for selection and study the rationale of their design decisions. Automated website synthesis saves time and effort in building websites for such designs.

Few models and theories are available to address computational website design. However, if we view websites as a form of information visualisation, we can borrow some findings from automated diagram design (Kamps, 1999) to serve as our experiment hypotheses. Some systems for automated diagram design have incorporated text to enhance user understanding of graphical visualisation (Mittal et al., 1996). This kind of multimodal visualisation should be applicable to website design. Expressiveness and effectiveness of graphical languages as proposed by Mackinlay (Mackinlay, 1986) are influential to later diagram visualisation models. Since then, source information characteristics (Roth and Mattis, 1990), user-defined task specification (Casner, 1991), and user-defined layout preferences (Mittal et al., 1996) were introduced into various models for automated diagram design.

This experiment aims to elicit preferences of designers or users about visualisation patterns, particularly the preferences for tables and trees in visualising causality information. The participants were given interactive tree and table generators so that they could explore some different ways of presenting causality information in tables and trees as the visualisation formats. The participants gave their preference ratings for the available designs, as well as their rationale (criteria) for their design decisions. The participants were also asked to take four cognitive tests, which focus on the aspects of visualisation and analogy-making. The relationships among preference ratings, rationale, and the results of cognitive tests were studied.

7.1.1 Preferences: Trees or Tables

It is our goal to see if people would prefer different representations to display the same information. In this case, we select trees and tables as the options for selection by users. Tree representations are commonly used to graphically represent causality in printed documents. The causal relations are normally represented by arrows or lines connecting causes and effects.

7.1.2 Rationale for Preferences

If people do prefer a representation, it would be interesting to see what rationale or criteria contribute to their preferences. We categorised common rationale/criteria mentioned in website design textbooks (Krug, 2000; Nielsen, 2000):

1. easy to learn: the users do not need much time and effort to understand how it works;
2. more visual: the users can understand through graphical illustrations;
3. more informative: the users can know more details;
4. more scalable: fewer changes are needed to handle more massive information;
5. more features represented: less characteristics (important information) are left out;
6. more suggestive: the users can understand without much guessing; and
7. more flexible: suitable for use in different situations.

As these seven rationales may not cover all possible rationales that are crucial to any particular preference, the experiment participants were asked (unprompted) for their rationale before seeing these seven rationales and then they were asked (prompted) to identify if any of these rationales were similar to their own rationales. They were also asked if any of their rationales was not covered by these seven rationales.

7.1.3 Cognitive Tests

Software designs should reduce users' cognitive load (Detienne, 2002).We hypothesise that participants prefer one design to other designs partially because the preferred design suits their cognitive abilities. If this is true, the cognitive abilities of the participants should be related to their preferences. The relationships among preferences of trees or tables, the cognitive test results of the participants, and rationale for their preferences were studied in this experiment. As it is impossible to test numerous cognitive factors in a single experiment, the participants were only tested on cognitive styles / abilities of visualisation and analogy-making, which we guessed were related to visual representations.

7.2 Objectives of the Experiment

The main objectives of this experiment are as follows:

1. To see if there is any different preference for tables or trees in representing the given information;
2. To see if different preferences are based on different priority in criteria/rationale;
3. To see if the preferences are related to the cognitive test results; and
4. To see if the importance ratings of design criteria/rationale are related to cognitive test results.

7.3 Materials and Methods

7.3.1 Participants

Sixty four students from the University of Edinburgh participated in the experiment and received cash (GBP 10) as a reward. They were randomly assigned to one of the two groups according to a pre-generated random sequence. Each group had 32 participants. The treatments of these two groups differ in the order of using table and tree design generators (or simply called designers). All of the participants had the computer skills for browsing websites. The experiment took about 1.5 hours for each participant. No strict time limit was enforced for tasks except cognitive tests, for which data were automatically collected.

7.3.2 Web Pages

Computational website synthesis provides basic facilities for generating web sites and their functional components such as menus and breadcrumbs. We just need to map the information content items to appropriate components in specifications. For example,

$$\begin{array}{|l}
\mathit{caseList}(\mathit{Cases}) \rightarrow \mathit{menu}(\mathit{MenuList}) \\
\hline
\mathit{filenames}(\mathit{Cases}, \mathit{MenuItems}, \mathit{Filenames}) \wedge \\
\mathit{menuItemize}(\mathit{MenuItems}, \mathit{Filenames}, \mathit{MenuList})
\end{array}$$

where $\mathit{caseList}(\mathit{Cases})$ provides a list of cases. The list of cases can be mapped to $\mathit{menu}(\mathit{MenuList})$ via the carriers to formulate filenames by adding prefixes and suffixes to the accident codes and to encode them in compliance with PiLLoW for presenting the menu shown on each web page. Presentation of accident event (content) information in visualisation formats (tabular cells or graphical trees) requires mappings of attributes between the content information and visualisation formats. One of the major factors affecting the mapping decision is designers' (and/or users') preferences.

Our approach to eliciting the designers' preference is to let the designers explore the available options and then decide which option is the one they prefer. For doing this, we give the information of the customised images (representing specific pieces of information) to a home-made drag-and-drop web component as parameters so that the users can design their preferred tables (Figure 7.1) and trees (Figure 7.2) by dragging and dropping the representational images (one at a time) in a position relative to any specific tiny (1x1 pixels) image dot (invisible). A drop of the representational image is successful only if it is dropped within an area of a predefined radius to the anchor image. If a representational image is dropped outside the specified area, then it will return to its original position. The repositioning will be activated whenever there is a change (e.g., change of window size which affects the relative positions of images). A piece of JavaScript code is generated to feed these parameters to a JavaScript component for image

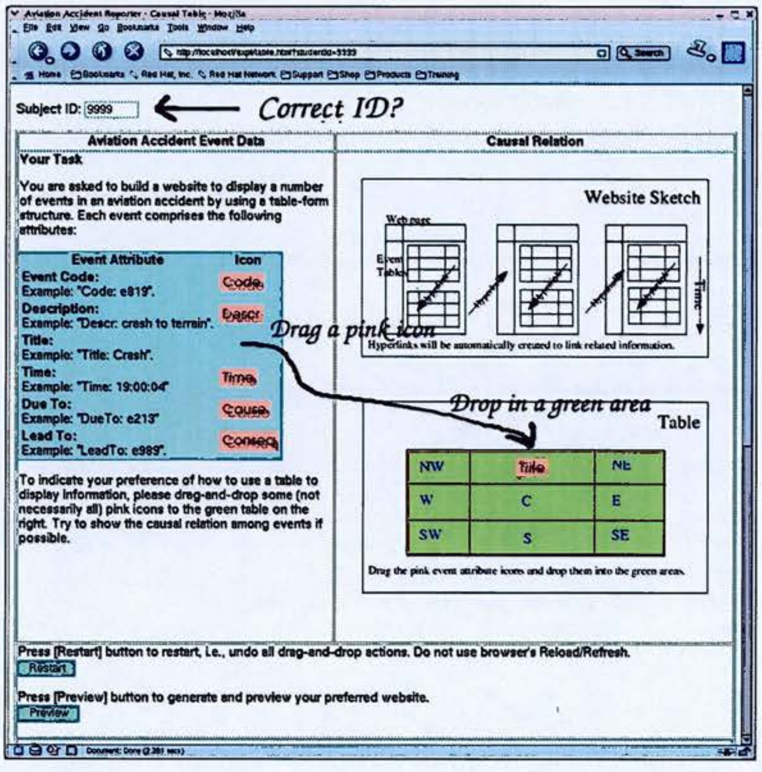


Figure 7.1: Exploring options for tabular representation

drag-and-drop management. This approach is simpler (lightweight) than many other approaches which use sophisticated (heavyweight) Java Applets or Flash objects to provide drag-and-drop functions.

7.3.3 Data Collection

All input from the participants were collected by standard HTML forms and CGI (common gateway interface) scripts, which were generated from simpler specifications for defining variables and variable types (e.g., multi-answers or long text) and special web page elements. Subsequent minor modifications to the generated questionnaire forms were only for cosmetic purposes.

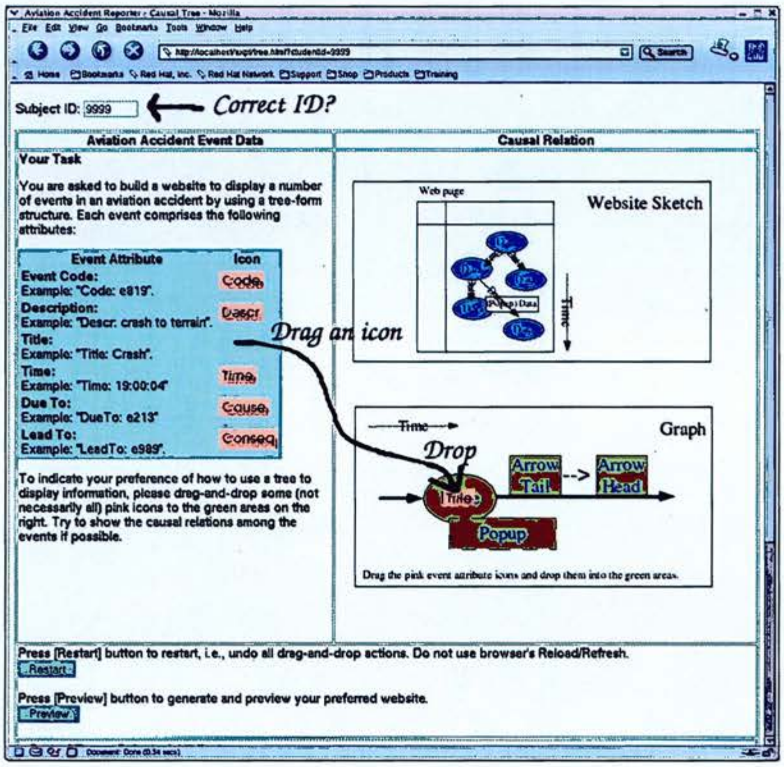


Figure 7.2: Exploring options for tree form representation

7.3.4 Tree and Table Generators

The trees and tables were generated on-the-fly and viewable in a separate window of the Web browser together with other basic website navigation facilities, e.g., menus and hyperlinks. The tables were generated as standard HTML tables while the trees were generated as DOT diagram specifications for final image rendering by GraphViz[1] on the server side before sending to the client side.

7.3.5 Tasks

Each participant filled in a pre-experiment questionnaire (Appendix B) which collected background information such as their familiarity with the Web and aviation operations. Then the participants used table and tree designers to express their preferences between tables and trees in representing a given structure of causality

[1]http://www.graphviz.org

information. The order of using table and tree designers were randomly assigned. Participants assigned to Group A used the tree designer first and then the table designer while those in Group B used the table designer first and then the tree designer. In the designers, the participants used a customised drag-and-drop facility to design their preferred table and tree patterns. The participants submitted their preferred visualisation patterns as tables or trees. Their rationale for their preferred visualisation pattern were collected by a two-part post-experiment questionnaire. Part A of the questionnaire collected their rationale as the open-ended answers and their preference ratings of table and tree visualisation. Part B of the questionnaire collected their ratings of the importance against seven common preference criteria/rationale. The participants also took timed cognitive tests, including two (paper folding and surface development) visualisation tests and two (visual and verbal) analogy-making tests. The visualisation tests were licensed from the Educational Testing Services of the USA, as provided in a kit of factor-referenced cognitive tests (Ekstrom et al., 1976). The visual analogy puzzles were the same as those selected by Thomas Evans (Evans, 1987) in his study of visual analogy problems. The verbal analogy test was the sample questions of the Miller Analogy Test[2] (MAT).

7.3.6 Data Analysis

Variables include (1) preference of tables or trees, (2) importance ratings of preference criteria/rationale, and (3) results of cognitive tests. They were analysed by Wilcoxon test, Krustal-Wallis test, and Kendall rank correlation test using R[3] statistical software (R Development Core Team, 2007) and its μStat package[4]. P values less than 0.05 were considered statistically significant.

[2] http://www.milleranalogies.com
[3] http://www.r-project.org
[4] http://mustat.rockefeller.edu

7.4 Results

7.4.1 Background of Participants

There was no significant difference in any background variable between two groups of participants as measured by the pre-experiment questionnaire (Appendix B) and analysed by Student's t-test and Wilcoxon test.

7.4.2 Preferences

Preferences were obtained from the preference ratings about participants' preferences between tables and trees as the representation of the given information. The participants rated the strength of their preferences as:

1. strong table preference,
2. moderate table preference,
3. marginal table preference,
4. marginal tree preference,
5. moderate tree preference, and
6. strong tree preference.

Based on the types of preferred representations, binary classification gives two categories of participants:

- table preferrers, and
- tree preferrers.

The number of participants under these classifications of preferences were counted as follows:

Preferences	Binary Class.	Count
Strong table	Table	3
Moderate table	Table	14
Marginal table	Table	6
Marginal tree	Tree	6
Moderate tree	Tree	15
Strong tree	Tree	20

23 participants preferred tables and 41 participants preferred trees.

7.4.3 Rationales

Seven rationales/criteria were given to the participants to rank using the numbers 1-7. Rank 1 is the most important rationale or criteria in their preference decision. Rank 7 is the least important one. The summary statistics including median, mean, and standard deviation (SD) of the overall ranking on the common design criteria/rationale is as follows:

Rationale	Median	Mean	SD
Easier to learn	3	3.09	2.01
More visual	4	4.06	1.78
More informative	2	2.78	1.86
More scalable	5	4.90	1.42
More features	5	4.86	1.90
More suggestive	4	3.98	2.00
More flexible	5	4.86	1.78

This overall result indicates that the participants found "more informative" and "easier to learn" as the most important two rationales for their preference decisions. "More visual" and "more suggestive" were moderately important.

7.4.4 Cognitive Tests

The summary statistics of the test results are as shown in Table 7.1.

The test of surface development visualisation seemed to be difficult to some participants. The median of the result was 0 and its standard deviation was high.

Table 7.1: Cognitive test results

Tests	Median	Mean	SD
Paper folding	5	5.33	2.24
Surface development	0	8.59	11.14
Visual analogy	17	15.89	3.88
Verbal analogy	8	9.97	7.49

7.4.5 Preferences and Rationales

As shown in Table 7.2, the differences in the rankings of the rationale "easier to learn" among different participants with different strengths of preferences were found statistically significant by using the Krustal-Wallis test. The difference between table preferrers' and tree preferrers' rankings of the rationale "easier to learn" was highly statistically significant as indicated by the Wilcoxon test.

Table 7.2: Preferences and rationale

Rationale	Preferences			Binary Preferences		
	χ^2	P		χ^2	P	
Easier to learn	11.88	0.037	*	9.22	0.002	**
More visual	7.37	0.195		1.60	0.207	
More informative	5.10	0.404		1.25	0.264	
More scalable	5.07	0.408		1.48	0.225	
More features	6.90	0.228		3.84	0.050	
More suggestive	7.37	0.194		5.69	0.017	*
More flexible	8.57	0.127		0.23	0.633	

* $P < 0.05$, ** $P < 0.01$

The significant difference related to the rationale "more suggestive" was only observed in binary preferences, not in the original classification of preferences and their strengths.

Table 7.3 showed the median rankings of rationale for preferences. Table preferrers found the criterion "easier to learn" to the most important rationale while the tree preferrers did not.

Table 7.3: Rankings of rationale by different preferrers

Rationale	Table Preferrers			Tree Preferrers		
	Median	Mean	SD	Median	Mean	SD
Easier to learn	1	2.13	1.74	4	3.63	1.96
More visual	3	3.74	1.79	4	4.24	1.79
More informative	3	3.04	1.99	2	2.63	1.80
More scalable	4	4.65	1.27	5	5.00	1.50
More features	6	5.65	0.98	5	4.42	2.14
More suggestive	5	4.78	1.86	3	3.54	1.94
More flexible	5	5.04	1.64	5	4.76	1.87

7.4.6 Preferences and Cognitive Tests

The relationship between the results of visual analogy test and preferences (and binary preferences) and was highly significant ($P < 0.01$) according to the Kruskal-Wallis test (and Wilcoxon test), as shown in Table 7.4. It was highly significant ($P < 0.01$) that the participants who performed better in the visual analogy test preferred trees (Table 7.5).

7.4.7 Rationale and Cognitive Tests

The correlation between the importance rankings of rationale ("easier to learn" and "more suggestive") and the result rankings of cognitive tests are statistically significant (Table 7.6) according to Kendall's rank correlation test.

The statistically significant rank correlations coefficient (τ) ranged between around 0.201 - 0.263, which are only low to moderate in strength.

Table 7.4: Cognitive test results and preferences

Tests	Preferences			Binary Preferences		
	χ^2	P		χ^2	P	
Paper folding	9.16	0.103		5.10	0.024	*
Surface development	6.09	0.298		0.15	0.697	
Visual analogy	16.36	0.006	**	13.50	0.000	**
Verbal analogy	3.95	0.557		1.14	0.286	

* $P < 0.05$, ** $P < 0.01$

Table 7.5: Cognitive test results of different preferrers

Tests	Table Preferrers			Tree Preferrers		
	Median	Mean	SD	Median	Mean	SD
Paper folding*	4	4.57	2.04	5	5.76	2.26
Surface development	0	7.61	11.16	0	9.15	11.22
Visual analogy**	16	13.57	5.66	17	17.2	1.14
Verbal analogy	9	9.96	6.47	7	9.98	8.08

* $P < 0.05$, ** $P < 0.01$

7.5 Discussion

This study used website synthesis to construct an experimental apparatus for Lab-on-the-Web. Using this approach we found a significant relationship among the participants' preferences, rationale, and cognitive ability test results. Most (41 out of 64) participants claimed themselves to be tree preferrers. The other participants (23 out of 64) said they preferred tables. Both table preferrers and tree preferrers found their preferred representations (tables or trees) more informative, without significant difference in rankings of this rationale. As the task given to the participants is to represent information, it is not surprising that the rationale "more informative" was one of the most important rationale. In further

Table 7.6: Correlation between rationale and cognitive test results

Tests	Easier to learn			More suggestive		
	τ	P		τ	P	
Paper folding	0.203	0.039	*	-0.050	0.608	
Surface development	0.173	0.088		-0.070	0.484	
Visual analogy	0.263	0.008	**	-0.201	0.040	*
Verbal analogy	0.006	0.948		0.058	0.532	

* $P < 0.05$, ** $P < 0.01$

studies, it would be interesting to test whether the participants find the same rationale justifiable for their preferences when they are given different goals or under different conditions. This might give us more insights into how different preferrers perceive information.

To table preferrers, the rationale "easier to learn" was more important than "more informative". The rationale "easier to learn" was ranked as the most important by 13 out of 23 table preferrers, but not so important by tree preferrers. Tree preferrers ranked the rationale "more suggestive" significantly higher than the table preferrers did. To table preferrers, tables seemed to be easier to learn than trees. To tree preferrers, trees were more suggestive than tables. These discrepancies in rationale ranking indicate a perception difference between different preferrers in perceiving the given tables and trees.

Tree preferrers performed better than table preferrers in some tests of cognitive factors, particularly the paper folding visualisation test and visual analogy test. There was no significant difference between table preferrers and tree preferrers in their performance in other cognitive tests including the surface development visualisation test and the verbal analogy test. It is plausible that the interpretation of tree representations requires specific cognitive capabilities such as visualisation and visual analogy-making; thus, those who do not feel comfortable with these tasks would prefer tables and highly rank the rationale "easier to learn" for their table preference.

Among all participants, there is a statistically significant low-to-moderate rank correlation between the rankings of the rationale "easier to learn" and the results of visual analogy test and paper folding visualisation test. The low-to-moderate rank correlation indicates that the participants who performed better in such two cognitive tests ranked the rationale "easier to learn" to be less important. At similar correlation strength, the participants who performed better in visual analogy test ranked the rationale "more suggestive" to be more important. It seems that the visualisation and visual analogy-making abilities of the participants might play a role in their preferences for tables and trees. Possibly (although we cannot prove this), table preferrers lack sufficient cognitive capability to interpret graphical representations like trees; thus, they prefer tables as they are easier to learn. Tree preferrers would feel more comfortable in making visual analogy and find graphical representations like trees suggestive. As indicated by the low to moderate strengths of correlation in these results, it is probable that other factors (and other cognitive factors) may be also relevant to the participants' preferences. Further studies are required to delineate these relationships.

In addition to the scientific findings, this experiment demonstrated the technological significance of computational synthesis in enabling scientific experiments. This experiment re-used a Website synthesiser (used in the experiment described in Chapter 6) to generate Websites on the fly so that the designers/users can explore the design space (see Section 7.3.2). Without using a Website synthesiser, this experiment would not be possible. Other than computational synthesis, the most relevant tool is Web content management system but it does not meet the requirement of this experiment. Apart from its high cost, there is no Web content management system so flexible as our our Website synthesiser in accepting information mappings. This makes Web content management systems inapplicable to our experiment. Thus, computational synthesis is the only available solution for this experiment.

7.6 Chapter Summary

The experiment reported in this chapter found significant relationships between the participants' design preference, rationale, and cognitive test performance. This work also exemplifies the use of a Website synthesiser as an essential instrument enabling the participants to explore different possible designs, which were generated on the fly, before they selected their preferred designs. Computational synthesis made this experiment possible.

Chapter 8

Significance and Further Work

This thesis presents a new use of computational synthesis for scientific experimentation, particularly synthesis from parameterisable components. We developed a grammar formalism to integrate useful knowledge representations for specifying the computational synthesis of (1) Websites according to our Simple Website Interface Model (SWiM) and (2) Web-based experiments according to a research script formulated from published empirical psychology research. To test the method, we used it to obtain scientific findings in novel experiments using synthetic Websites. This allowed us to conduct the first extensive tests of causal perception theories on the Web. We also used the Website synthesiser as an instrument to allow participants to generate Websites on-the-fly and to find their own preferred design of Websites to present aviation accident events. Their design preferences were found to be moderately related to specific cognitive factors including visualisation and visual analogy-making. These Web-based experiments, due to the large amount of labour in constructing a wide variety of Websites, would not be feasible without using computational synthesis. This chapter summarises the major results and contributions of current research, as well as their broader significance for computational synthesis, particularly of Websites and experiments, in scientific experimentation.

8.1 Contributions

8.1.1 Knowledge Representation

Our style of computational synthesis makes use of an integrative grammar formalism (morganic grammars) as described in Chapter 3. Morganic grammars provide (1) grammatical categories (morgans) with frame-like attribute-value matrices, (2) carriers to specify bridging the conceptual gaps between morgans, and (3) conditional rewriting.

8.1.2 Website Synthesis

A Simple Website Interface Model (SWiM) was proposed (Chapter 4) to provide conceptual, structural, and layout frameworks for overall grammatical development of Website synthesis. With the framework of SWiM summarising suitable Website design practices for computational synthesis, Website synthesis should be easy to learn by Website designers and programmers.

8.1.3 Experiment Synthesis

As a wide-spectrum language, morganic grammars are useful to represent experiments and their materials/instruments. For experiment synthesis, we follow a result (a research script) from empirical psychology research into how scientists formulate their experimental research. According to this research script, we can specify and synthesise computational parts of experiments, particularly specifying experimental parameters and Web-based materials for experimental treatments (Chapter 5).

8.1.4 Causal Perception Experiment

We used computational synthesis of Websites and experiments to approach an important issue of cognitive science, i.e., causal perception based on the covariation of the information about cause candidates and effects (Chapter 6). By using aviation accident reporting as a test domain, we found that covariation of the information is more influential than the rhetorics (e.g., temporal or causal order in presentation of events) and understandability (e.g., whether the technical terminology is cryptic) to the perception of causality between cause candidates and effects (accidents). The experiment results (causal ratings) are close to the predicted results by PowerPC theory. Without Website synthesis, this experiment would not be affordable in time and effort to provide the necessary combinatoric Website features. In addition to the scientific significance of this experiment to cognitive science, this experiment inspired us to develop computational synthesis for Web-based experiments. It also demonstrated the technological significance of computational synthesis in making the experiments like this one highly practical and easily affordable.

8.1.5 Design Preference Experiment

Tables and graphs are two major formats of information presentation, including the presentation on the Websites. The selection between these two formats is often subject to the preferences of designers and users. Rationales might explain a little (but not much) about the subjective preferences. Therefore we seek understanding from cognitive science. We found significant differences in cognitive factors (including visualisation and visual analogy-making abilities) between table and graphic tree preferrers. The differences in these cognitive factors provide a possible reason to explain the subjective preferences. Further research into the relationship between cognitive factors and design preferences would be fruitful. Without a Website synthesiser, the participants would not be able to explore different mappings between source information and presentation formats. Thus, in addition to the scientific significance of this experiment to cognitive science, this experiment demonstrated the technological significance of computational synthesis in making the experiments like this one possible.

8.2 Broader Significance

8.2.1 Facilitating Scientific Experimentation

The present work provides arguments for the necessity of experiment synthesis in scientific research and evidence for the feasibility of a specific style of experiment synthesis, thus pioneering research into computational synthesis of Web-based experiments. Our use of synthetic Websites and experiments obtained new scientific findings about the cognitive features of causal perception and design preference.

Synthetic Websites and experiments are more affordable than the Websites and experiments manually constructed. Morganic grammars provide a more systematic approach than conventional Web scripting to generate Websites. As science relies on experimentation to make progress (see Chapter 2), our results in Website synthesis and experiment synthesis are encouraging to scientists who are able by this means to do more experiments in a more affordable and systematic manner. As synthetic experiments are more affordable and formally specified, reproducibility of the experiments would be easier to achieve.

Following our method, before and during experiment synthesis, scientists must first find suitable and affordable instruments and experiment toolkits, which are readily available materials specially designed for experimental purposes. Even if there are some suitable and affordable instruments and toolkits, it would still be difficult for scientists to find all required facilities for their creative experiments. They may need to formulate their own experiments by modifying and recombining components of past experiments. In special cases, scientists need to invent and construct their own experiment facilities to meet the experiment requirements. Morganic grammars may be useful to integrate various components such as hypotheses (theoretical constructs), treatments, measurements, experiment units, experiment design, and data analysis. All these would facilitate experiment synthesis to create new or to reproduce/reuse the materials and protocols of the experiments already synthesised.

8.2.2 Enabling Technology for Lab-on-the-Web

Ideally an experiment specification based on the initial morgan (e.g., Figure 5.1) would be used to construct new instruments or setting parameters to control readily available instruments for treatments, controls, and measurements. Instruments are essential to experiment synthesis in the Lab-on-the-Web. These instruments can then be used to model knowledge, provide working knowledge, and/or conduct measurements (Baird, 2003). The instruments that model knowledge facilitate denotation, demonstration, and/or interpretation of the knowledge.

The instruments that provide working knowledge perform or exhibit phenomena, for which there is no adequate theoretical knowledge, regularity, and reliability. The instruments that conduct measurements collect the data required by experiments. It is expected that the instruments available in the Lab-on-the-Web are supplied through the Web or are part of the Web itself. The Web can thus serve as a versatile experimental instrument.

8.3 Further Work

Much more work than this thesis is to be done to facilitate scientific experimentation and to develop Lab-on-the-Web. This section describes some ideas for improving and then extending the current work.

8.3.1 Formalising Morganic Grammars

Morganic grammars were developed as a pragmatic, integrative knowledge representation for representing the transformation rules for Website synthesis and experiment synthesis. There is overlap between our style of knowledge representation and other styles, for example feature-based unification grammars using attribute-value matrices and conditional rewrites using explicit rewrite rules. Formalisation of morganic grammars may clarify the differences between morganic grammars and other knowledge representations, e.g., other grammar formalisms (including DCGs) and frames/object-oriented representations. The results may also suggest what kinds of concepts should be better represented by morgans, rewrites, or carriers.

8.3.2 Experimenting with Rewriting Approaches

We have not yet tried different strategies for rewriting grammar rules. It would be nice to explore and evaluate different rewriting strategies in formulating Websites and experiments. In addition to pure synthesis, we can experiment with combined parsing and generation to automate experimentation based on the hypotheses specified in grammar rules. This would enable cycles of automated experimentation as an active learning process.

8.3.3 Supporting Hypothesis Formulation

Hypothesis generation is mysterious and it seems there is no promising theory to help automate it. In psychology, William McGuire has been working on finding heuristics for hypothesis generation (McGuire, 1997). For teaching graduate students, he also developed a structured (and probably the most sophisticated so far) questionnaire / worksheet to facilitate hypothesis generation (McGuire, 2004b) and theory construction (McGuire, 2004a). Interestingly, the syntax of his basic, abstract notation is:

$IV \rightarrow DV$

$IV \rightarrow MV$

$MV \rightarrow DV$

where IV is independent variables, MV is mediating variables, and DV is dependent variables. His notations resemble grammar rules. Morganic grammars may be useful to specify the parameters (features) to facilitate his theoretical system of hypothesis generation.

8.3.4 Extending Hypotheses for Further Experiments

Like most of the published psychology and cognitive science experiments, we could not conduct random sampling with a larger population of subjects. We should conduct similar (not necessarily the same) experiments to extend our experiments for understanding causal perception and design preference. For example, we have not yet investigated whether temporal and causal rhetorics in graphics form would affect causal perception. We have not yet tested many other cognitive factors which might be also related to design preference. It would be even better to use morganic grammars to generate systematic hypotheses and test McGuire's heuristics for hypothesis generation.

8.3.5 Communicating for Coordinated Experimentation

We cannot individually do numerous [even if synthetic or computational] experiments using only our personal limited resources and expertise. Collaboration is necessary for better research. Experiment synthesis alone does not expedite experimentation in collaborative research. A substantial collaborative research project may run extensive experiments which require different resources and expertise. A single specialised laboratory in the collaborative research may only run a small number of synthetic experiments. To make a significant contribution to science, the experiment hypotheses and results must be communicated for coordinated experimentation. Compatible formal languages to support collaborative knowledge sharing are now being made available, for example the Lightweight Coordination Calculus (LCC) from the OpenKnowledge[1] project might be used to facilitate coordination among laboratories.

8.3.6 Developing Ontologies of Websites and Experiments

Few ontologies are readily available for use because of the high cost in development and maintenance of ontologies. In the early stages of our research we developed an ontology of aviation accident reporting by using Protege 2000 based on the Harmonisation of European Incident Definition (HEIDI) database schemas. The ontology, which turned out not to be essential to current research, is as shown in Figure 8.1. We still believe that, despite the high cost, a more fully developed ontology of aviation accidents and an ontology of Websites would expedite the synthesis of aviation accident Websites. Another ontology we would like to develop through collaboration is an ontology of cognitive science experiments. As far as we know, there is one for bioinformatics experiments (Soldatova et al., 2006) but it is not yet widely used. In our experiments, we only have the basic parameters (variables) for specification. Other aspects such as the instruments (and their parameters) and data analysis are unavailable. Although the development of these kinds of ontologies is now a huge consensual task, it may become more feasible if many people participate via collaborative development tools.

8.3.7 Sketching for High Fidelity Website Prototypes

Sketching is thought helpful for developing design ideas. For Website design, a prototyping tool DENIM[2] allowing designers to sketch for Website design is available. It would be interesting to integrate the conceptual models of DENIM and SWiM. We might be able to apply Website synthesis to rapid prototyping

[1] `http://www.openk.org`
[2] `http://dub.washington.edu/projects/denim`

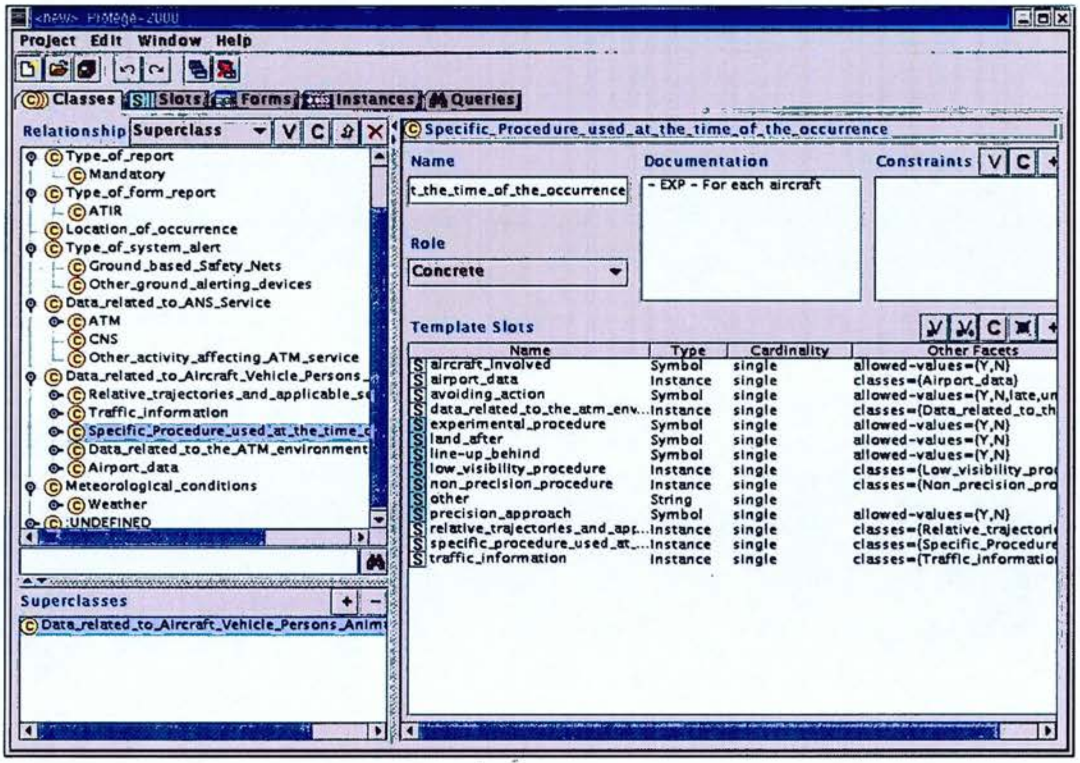


Figure 8.1: Ontology development using HEIDI definitions of aviation accidents

of DENIM. Hopefully, designers sketch their preferred Website as a low-fidelity prototype using a tool like DENIM and then produce high-fidelity prototypes immediately using Website synthesis.

8.4 Concluding Remarks

The research described in this thesis contributes to our understanding of computational synthesis of Websites and experiments, by which we obtained new scientific findings. It has a broader significance in facilitating scientific experimentation and enabling the development of Lab-on-the-Web, in which the Web serves as an experimental instrument and/or interface with various kinds of instruments. It also stimulates some plausible ideas for further research into related areas.

Appendix A

Prolog Code for Rewriting

```
exhaustiveRewrite(Type, Term, FinalTerm) :-
    nonvar(Term),
    canRewrite(Type, Term), !,
    applyRewrite(Type, Term, NewTerm),
    exhaustiveRewrite(Type, NewTerm, FinalTerm).
exhaustiveRewrite(Type, Term, FinalTerm) :-
    \+ atomic(Term),  nonvar(Term),
    Term =.. [F|Args], !,
    exhaustiveRewriteArgs(Type, Args, FinalArgs),
    FinalTerm =.. [F|FinalArgs].
exhaustiveRewrite(_, Term, Term).

exhaustiveRewriteArgs(Type, [Term|T], [NewTerm|R]) :-
    exhaustiveRewrite(Type, Term, NewTerm),
    exhaustiveRewriteArgs(Type, T, R).
exhaustiveRewriteArgs(_, [], []).

canRewrite(Type, Term) :-
    applyRewrite(Type, Term, _).

applyRewrite(Condition, Term, NewTerm) :-
    PredCall =.. [Condition, Term, NewTerm], !,
    call(PredCall).
```

Appendix B

Pre-Experiment Questionnaire

This Appendix contains a pre-experiment questionnaire, which was used in the first task of the participants in both causal perception experiment (Chapter 6) and design preference experiment (Chapter 7). This questionnaire aims to get some ideas about the background experience of participants in using computer and understanding aviation accidents.

Pre-experiment Questionnaire

You will be asked some questions about your acquaintance with World-wide Web (referred to below as "the web") and your preferences in regard to it.

How many hours per week do you use computers?

How many hours per week do you use the web?

How many hours per week do you use the Internet but not through a web browser?

I prefer the web to other media when I look for information

- ○ Almost every time
- ○ About 80-99% of cases
- ○ About 60-80% of cases
- ○ About 40-60% of cases
- ○ About 20-60% of cases
- ○ About 1-20% of cases
- ○ Almost never

I try the web first if I need information

- ○ Almost every time
- ○ About 80-99% of cases
- ○ About 60-80% of cases
- ○ About 40-60% of cases
- ○ About 20-40% of cases
- ○ About 1-20% of cases
- ○ Almost never

I experience disorientation in navigating the web

- O Almost every time
- O About 80-99% of cases
- O About 60-80% of cases
- O About 40-60% of cases
- O About 20-40% of cases
- O About 1-20% of cases
- O Almost never

I am experienced in designing a good homepage

- O Highly experienced
- O Very experienced
- O Somewhat experienced
- O Done before but not experienced
- O Know something but no hands-on experience
- O None

I am experienced in administrating a web server

- O Highly experienced
- O Very experienced
- O Somewhat experienced
- O Done before but not experienced
- O Know something but no hands-on experience
- O None

How many hours of experience do you have in designing web pages for other people (including profitable and non-profitable services)?

- O More than 1000 hours
- O 501 - 1000 hours
- O 101 - 500 hours
- O 51 - 100 hours
- O 1 - 50 hours
- O Less than 1 hour

How would you prefer to find information on the web?

- ○ I want to search for keywords
- ○ I want links presented alphabetically
- ○ I want links categorized hierarchically
- ○ I want to ask questions in clear text
- ○ I want the computer to ask me questions and direct me
- ○ None of the above

How many hours of experience do you have in playing with aviation game software? [ ]

I am familiar with aviation operations

- ○ I know almost everything in aviation operations
- ○ I know as much as an air-traffic controller do
- ○ I know more than amateurs do
- ○ I know as much as amateurs do
- ○ I know more than laymen do
- ○ I know as much as most laymen do
- ○ Not at all

Have you ever received any formal training in civil or military aviation operations?

- ○ Yes
- ○ No

Are you male or female?

- ○ Male
- ○ Female

In which year were you born (e.g., 1975)? [ ]

Which study programme do you belong to?

Your name:

Your Subject ID:

Please click on the Submit button to submit your answers:

Submit

Click on the Clear button if you want to clear all of your answers.

Clear

Appendix C

Post-Experiment Questionnaire (Design Preference)

This Appendix contains Parts A and B of the questionnaire used in design preference experiment (Chapter 7) after the participants explored different possible designs. The participants answered the questions of Part A before reading Part B. This questionnaire asks about the participants' preference and rationale in selecting forms of design (tables or trees).

Questionnaire about preference (Part A)

You will be asked some questions about your preferences in regard to the display of the given causality information in this experiment.

Which do you prefer in displaying the given causality information in this experiment?

- ○ strongly prefer tables
- ○ moderately prefer tables
- ○ slightly prefer tables
- ○ slightly prefer trees
- ○ moderately prefer trees
- ○ strongly prefer trees

What are the reasons for your preference? Please explain.

Your Subject ID:

Submit Clear

Questionnaire about preference (Part B)

You will be asked some further questions about your preference in web design.

Have any of these criteria been mentioned (even if using different terms) in the explanation of your preference? (Multiple answers are allowable) Your preferred design is:

- ☐ easier to learn by the users
- ☐ more visual
- ☐ more informative
- ☐ easier to scale up for a bigger size of information
- ☐ preserving more features of the source information
- ☐ more suggestive for correct interpretation
- ☐ more flexible to users

Have any of these criteria been considered (even though not explicitly mentioned in the explanation of your preference)? (Multiple answers are allowable) Your preferred design is:

- ☐ easier to learn by the users
- ☐ more visual
- ☐ more informative
- ☐ easier to scale up for a bigger size of information
- ☐ preserving more features of the source information
- ☐ more suggestive for correct interpretation
- ☐ more flexible to users

Please rank (1-7) these criteria according to their relevance to a good design in your opinion. The most relevant criterion should be ranked as 1. The least relevant criterion should be ranked as 7. The answers should be entered in the boxes. A preferred design should be:

- [ ] easier to learn by the users
- [ ] more visual
- [ ] more informative
- [ ] easier to scale up for a bigger size of information
- [ ] preserving more features of the source information
- [ ] more suggestive for correct interpretation
- [ ] more flexible to users

Please describe any better criteria for a good design to display the information.

Your Subject ID:

Submit Clear

Bibliography

Baird, D. (2003). Thing knowledge: outline of a materialist theory of knowledge. In Radder, H., editor, *The Philosophy of Scientific Experimentation*, chapter 3, pages 39–67. University of Chicago Press.

Barnes, B., Bloor, D., and Henry, J. (1996). *Scientific Knowledge: A Sociological Analysis*. The University of Chicago Press.

Bartlett, F. (1995). *Remembering: A Study in Experimental and Social Psychology*. Cambridge University Press, 2nd revised edition.

Basili, V., Shull, F., and Lanubile, F. (1999). Building knowledge through families of experiments. *IEEE Transaction on Software Engineering*, 25(4):456–473.

Birnbaum, M. (2004). Human research and data collection via the internet. *Annual Review of Psychology*, 55:803–832.

Blackburn, P., van Benthem, J., and Wolter, F., editors (2006). *Handbook of Modal Logic*. Studies in Logc and Practical Reasoning. Elsevier.

Boeckx, C. (2006). Generative grammars and modern cognitive science. *Journal of Cognitive Science*, 6(1):45–54.

Borwein, J. and Bailey, D. (2003). *Mathematics by Experiment: Plausible Reasoning in the 21st Century*. AK Peters.

Brachman, R. and Levesque, H. (2003). *Knowledge Representation and Reasoning*. Morgan Kaufmann.

Buehner, M. and May, J. (2003). Rethinking temporal contiguity and the judgement of causality: Effects of prior knowledge, experience, and reinforcement procedure. *The Quarterly Journal of Experimental Psychology*, 56A(5):865–890.

Cabeza, D. and Hermenegildo, M. (2001). Distributed WWW programming using (Ciao-)Prolog and the PiLLoW library. *Theory and Practice of Logic Programming*, 1(3):251–282.

Campbell, D. and Russo, M. (1999). *Social Experimentation.* Sage Publications.

Carpenter, B. (1992). *The Logic of Typed Feature Structures.* Cambridge University Press.

Carpineto, C. and Romano, G. (2004). *Concept Data Analysis.* John Wiley & Sons.

Casner, S. (1991). A task-analytic approach to the automated design of graphic presentations. *ACM Transactions on Graphics*, 10(2):111–151.

Cavalcanti, J. and Robertson, D. (2000). Synthesis of Web sites from higher level descriptions. In *The Third Workshop on Web Engineering*, Amsterdam, The Netherlands.

Cavalcanti, J. and Robertson, D. (2003). Web site synthesis based on computational logic. *Knowledge and Information Systems*, 5(3):263–287.

Cheng, P. and Holyoak, K. (1985). Pragmatic reasoning schemas. *Cognitive Psychology*, 17:391–416.

Cheng, P. and Novick, L. (1990). A probabilistic contrast model of causal induction. *Journal of Personality and Social Psychology*, 58:545–567.

Chomsky, N. (1980). *Rules and Representations.* Columbia University Press.

Coolican, H. (1990). *Research Methods and Statistics in Psychology.* Hodder and Stoughton.

Copestake, A. (2002). *Implementing Typed Feature Structure Grammars.* Center for the Study of Language and Information.

Cox, D. and Reid, N. (2000). *The Theory of the Design of Experiments*, volume 86 of *Monographs on Statistics and Applied Probability.* Chapman and Hall/CRC.

Czarnecki, K. and Eisenecker, U. (2000). *Generative Programming: Methods, Tools, and Applications.* Addison-Wesley.

Detienne, F. (2002). *Software Design – Cognitive Aspects.* Springer-Verlag. I.

Do, H., Elbaum, S., and Rothermel, G. (2005). Supporting controlled experimentation with testing techniques: an infrastructure and its potential impact. *Empirical Software Engineering*, 10:405–435.

Ekstrom, R., French, J., and Harmon, H. (1976). *Manual for kit of factor-referenced cognitive tests.* Educational Testing Service.

Evans, T. (1987). A heuristic program to solve geometric-analogy problems. In *Readings in computer vision.* Morgan Kaufmann.

Falmagne, R. and Gonsalves, J. (1995). Deductive inference. *Annual Reviews of Psychology*, 46:525–559.

Feyerabend, P. (1978). *Against Method.* Verso.

French, J., Ekstrom, R., and Price, L. (1963). *Kit of Reference Tests for Cognitive Factors.* Educational Testing Services.

Fugelsang, J., Stein, C., Green, A., and Dunbar, K. (2004). Theory and data interactions of the scientific mind: evidence from the molecular and the cognitive laboratory. *Canadian Journal of Experimental Psychology*, 58(2):86–95.

Fugelsang, J. and Thompson, V. (2000). Strategy selection in causal reasoning: when beliefs and covariation collide. *Canadian Journal of Experimental Psychology*, 54(1):15–32.

Fugelsang, J. and Thompson, V. (2001). Belief-based and covariation-based cues affect causal discounting. *Canadian Journal of Experimental Psychology*, 55(1):70–76.

Fugelsang, J. and Thompson, V. (2003). A dual-process model of belief and evidence interactions in causal reasoning. *Memory & Cognition*, 31(5):800–815.

Fugelsang, J., Thompson, V., and Dunbar, K. (2006). Examining the representation of causal knowledge. *Thinking & Reasoning*, 12(1):1–30.

Gallagher, S. (2004). Hermeneutics and the cognitive sciences. *Journal of Consciousness Studies*, 11(10-11):162–174.

Ganter, B. and Willie, R. (1999). *Formal Concept Analysis - Mathematical Foundations.* Springer-Verlag.

Garrett, J. (2003). *The Elements of User Experience.* New Riders.

Gazdar, G. and Mellish, C. (1989). *Natural Language Processing in Prolog.* Addison-Wesley.

Gillies, D. (1996). *Artificial Intelligence and Scientific Method.* Oxford University Press.

Glymour, C. (2001). *The Mind's Arrows: Bayes Nets and Graphical Models in Psychology.* MIT Press. ISBN 0262072203.

Godfrey-Smith, P. (2003). *Theory and Reality.* The University of Chicago Press.

Grafen, A. and Hails, R. (2002). *Modern Statistics for the Life Sciences.* Oxford University Press.

Griffiths, P. (2006). *HTML Dog: The Best Practice Guide to HTML and CSS.* New Riders.

Haack, S. (1995). *Evidence and Inquiry.* Blackwell.

Haack, S. (2004). *Defending Science – Within Reason.* Prometheus Books.

Hershey, D., Jacobs-Lawson, J., and Wilson, T. (2006). Research as a script. In Leong, F. and Austin, J., editors, *The Psychology Research Handbook.* Sage Publications.

Hershey, D., Wilson, T., and Mitchell-Copeland, J. (1996). Conception of the psychological research process: script variation as a function of training and experience. *Current Psychology*, 14:293–312.

Hilton, D. (2002). Thinking about causality: pragmatic, social, and scientific rationality. In Carruthers, P., Stich, S., and Siegal, M., editors, *The Cognitive Basis of Science*, chapter 11, pages 211–231. Cambridge University Press.

Holyoak, K. and Morrison, R., editors (2005). *The Cambridge Handbook of Thinking and Reasoning.* Cambridge University Press.

Holyoak, K. and Spellman, B. (1993). Thinking. *Annual Reviews of Psychology*, 44:265–315.

Hunt, E. (1989). Cognitive science: definition, status, and questions. *Annual Reviews of Psychology*, 40:603–629.

Ioannidis, J. (2005). Why most published research findings are false. *PLoS Medicine*, 2(8):e124.

Jin, Y. (1983). *On Knowledge.* Commercial Press (China).

Jurafsky, D. and Martin, J. (2003). *Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics and Speech Recognition.* Prentice-Hall.

Kamps, T. (1999). *Diagram Design.* Springer-Verlag.

Krug, S. (2000). *Don't Make Me Think: A Common Sense Approach to Web Usability.* New Riders.

Kuhn, T. (1962). *The Structure of Scientific Revolutions.* University of Chicago Press.

Lakatos, I. (1977). *The Methodology of Scientific Research Programmes.* Cambridge University Press.

Lange, R. (2003). Technology as basis and object of experimental practices. In Radder, H., editor, *The Philosophy of Scientific Experimentation*, chapter 6, pages 119–137. University of Chicago Press.

Laudan, J. (1978). *Progress and Its Problems: Towards a Theory of Scientific Growth*. University of California Press.

Leonard, R. and Fontaine, P., editors (2005). *The Experiment in the History of Economics*. Routledge.

Leong, F. and Austin, J., editors (2006). *The Psychology Research Handbook*. Sage Publications, 2nd edition.

Leung, S. (1993). Basic Gene Grammars and DNA-Chartparser. Master's thesis, Department of Artificial Intelligence, University of Edinburgh.

Leung, S., Mellish, C., and Robertson, D. (2001). Basic Gene Grammars and DNA-ChartParser for language processing of *Escherichia coli* promoter DNA sequences. *Bioinformatics*, 17(3):226–236.

Leung, S. and Robertson, D. (2003). Automated website synthesis. In *Linux Developers' Conference*, Edinburgh, United Kingdom.

Leung, S., Zhang, Y., Robertson, D., and Shaw, P. (2004). A computational linguistics approach to representation and reasoning of DNA microarray experiments – with applications in medicinal plant and formulation authentication (poster). In *Intelligent Systems for Molecular Biology*, Glasgow, United Kingdom.

Lien, Y. and Cheng, P. (2000). Distinguishing genuine from spurious cause: a coherence hypothesis. *Cognitive Psychology*, 40:87–137.

Lovibond, P., Been, S., Mitchell, C., Bouton, M., and Frohardt, R. (2003). Forward and backward blocking of causal judgement is enhanced by additivity of effect magnitude. *Memory & Cognition*, 31(1):133–142.

Lowry, M. and Duran, R. (1989). Knowledge-based software engineering. In *The Handbook of Artificial Intelligence*, volume IV, chapter 20, pages 241–322. Prentice-Hall.

Lowry, M. and Van Baalen, J. (1997). Meta-amphion: synthesis of efficient domain-specific program synthesis systems. *Automated Software Engineering*, 4:199–241.

Mackinlay, J. (1986). *Automatic Design of Graphical Presentations.* PhD thesis, Computer Science Department, Stanford University.

Mandel, D. (2003). Effect of counterfactual and factual thinking on causal judgements. *Thinking and Reasoning*, 9(3):245–265.

Maxwell, J. (2004). Causal explanation, qualitative research, and scientific inquiry in education. *Educational Researcher*, 33(2):3–11.

McDermott, D. (1987). Logic, problem solving, and deduction. *Annual Reviews of Computer Science*, 2:187–229.

McGuire, W. (1997). Creative hypothesis generating in psychology: some useful heuristics. *Annual Reviews of Psychology*, 48:1–30.

McGuire, W. (2004a). A perspectivist approach to theory construction. *Personality and Social Psychology Review*, 8(2):173–182.

McGuire, W. (2004b). Perspectivist worksheets for generating a program of research. In Jost, J., Banaji, M., and Prentice, D., editors, *Perspectivism in Social Psychology*, pages 319–322. American Psychological Association.

Minsky, M. (1975). A framework for representing knowledge. In Winston, P., editor, *The Psychology of Computer Vision.* McGraw-Hill.

Mittal, V., Roth, S., Moore, J., Mattis, J., and Carenini, G. (1996). Generating explanatory captions for information graphics. In *Proceeedings of the International Joint Conference on Artificial Intelligence*, volume 2, Montreal, Canada.

Mizuno, R. (2004). *Laboratory (Web-based) Experiments on Basic Cognitive Psychology.* Nakanishiya (Japan).

Montgomery, D. (2005). *Design and Analysis of Experiments.* John Wiley & Sons, 6th edition.

Muller, P. (2007). *Little Boxes: Webseiten gestalten mit CSS.* Markt+Technik Verlag.

Neisser, U. (1976). *Cognition and Reality: Principles and Implications of Cognitive Psychology.* WH Freeman.

Nielsen, J. (2000). *Designing Web Usability: The Practice of Simplicity.* New Riders.

Oestermeier, U. and Hesse, F. (2000). Verbal and visual causal arguments. *Cognition*, 75:65–104.

Patzer, G. (1996). *Experiment Research Methodology in Marketing: Types and Applications.* Greenwood Press.

Penn, D. and Povinelli, D. (2007). Causal cognition in human and nonhuman animals: a comparative, critical review. *Annual Review of Psychology*, 58:97–118.

Piaget, J. (1971). *Biology and Knowledge: An Essay on the Relations Between Organic Regulations and Cognitive Processes.* University of Chicago Press.

Popper, K. (1959). *The Logic of Scientific Discovery.* Routledge, 2002 edition.

R Development Core Team (2007). *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria.

Radder, H. (2003). Technology and theory in experimental science. In Radder, H., editor, *Philosophy of Scientific Experimentation*, chapter 8, pages 152–173. University of Chicago Press.

Robertson, D. and Agusti, J. (1999). *Software Blueprints: Lightweight Uses of Logic in Conceptual Modelling.* Addison Wesley/ACM Press.

Robertson, D., Bundy, A., Muetzelfeldt, R., Haggith, M., and Uschold, M. (1991). *Eco-Logic: Logic-Based Approaches to Ecological Modelling.* MIT Press.

Roth, S. and Mattis, J. (1990). Data characterization for graphic presentation. In *Conference on Human Factors in Computing Systems (CHI).*

Ryan, T. (2007). *Modern Experimental Design.* John Wiley & Sons.

Sahdra, B. and Thagard, P. (2003). Procedural knowledge in molecular biology. *Philosophical Psychology*, 16(4):477–498.

Scaife, M. and Rogers, Y. (1996). External cognition: how do graphical representations work? *International Journal of Human-Computer Studies*, 45:185–213.

Shadish, W., Cook, T., and Campbell, D. (2002). *Experimental and Quasi-Experimental Designs for Generalized Causal Inference*. Hougton Mifflin.

Shull, F., Basili, V., Carver, J., Maldonado, J., Travassos, G., Mendonca, M., and Fabbri, S. (2002). Replicating software engineering experiments: addressing the tacit knowledge problem. In *Proceedings of the 2002 International Symposium on Empirical Software Engineering*, pages 7–16.

Shull, F., Mendonca, M., Basili, V., Carver, J., Maldonado, J., Fabbri, J., Travassos, G., and Ferreira, M. (2004). Knwoledge-sharing issues in experimental software engineering. *Empirical Software Engineering: An International Journal*, 9(1):111–137.

Skitka, L. and Sargis, E. (2006). The internet as psychology laboratory. *Annual Review of Psychology*, 57:529–555.

Smith, N. (1999). *Chomsky: Ideas and Ideals*. Cambridge University Press.

Soldatova, L., Clare, A., Sparkes, A., and King, R. (2006). An ontology for a robot scientist. *Bioinformatics*, 22(14):464–471.

Sowa, J. (2000). *Knowledge Representation: Logical, Philosophical, and Computational Foundations*. Brooks/Cole.

Stary, C. and Peschl, M. (1998). Representation still matters: cognitive engineering and user interface design. *Behaviour and Information Technology*, 17(6):338–360.

White, P. (2000). Causal attribution and Mill's methods of experimental inquiry: past, present and prospect. *British Journal of Social Psychology*, 19:429–447.

White, P. (2002). Perceiving a strong causal relation in a weak contingency: further investigation of the evidential evaluation model of causal judgement. *The Quarterly Journal of Experimental Psychology*, 55A(1):97–114.

White, P. (2003). Causal judgement as evaluation of evidence: the use of confirmatory and disconfirmatory information. *The Quarterly Journal of Experimental Psychology*, 56A(3):491–513.

Woodward, J. (2003). Experimentation, causal inference, and instrumental realism. In Radder, H., editor, *The Philosophy of Scientific Experimentation*, chapter 5, pages 87–118. University of Chicago Press.

Zhang, J. (1996). A representational analysis of relational information displays. *International Journal of Human-Computer Studies*, 45(1):59–74.

Zhang, J. (1997a). Distributed representations as a principle for the analysis of cockpit information displays. *The International Journal of Aviation Psychology*, 7(2):105–121.

Zhang, J. (1997b). The nature of external representations in problem solving. *Cognitive Science*, 21(2):179–217.